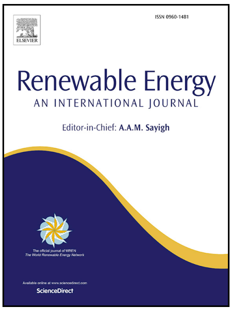

Techno-economic assessment of biomass gasification-based mini-grids for productive energy applications: The case of rural India

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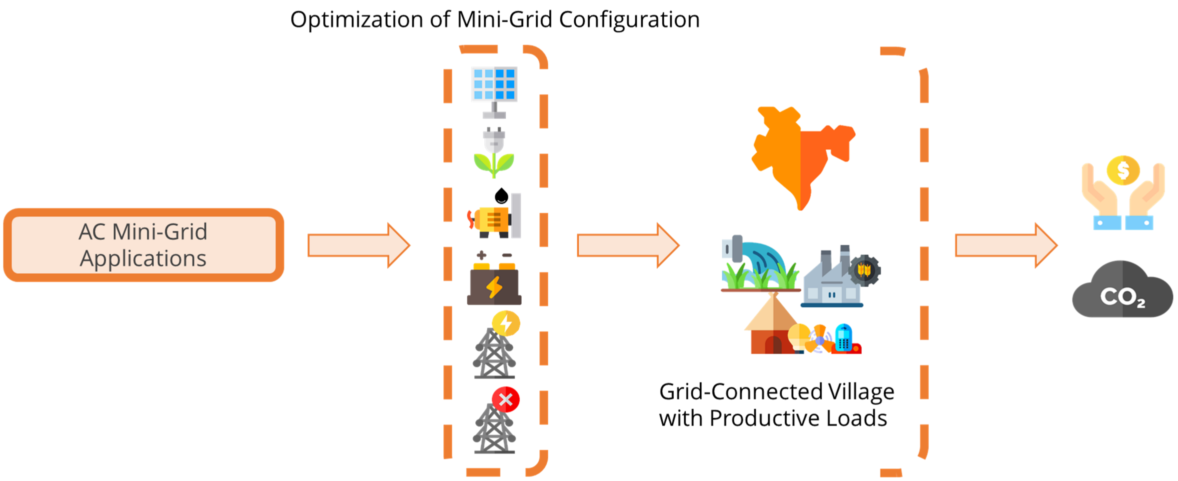
Chambon: Formal analysis; Methodology; writing original draft

Karia: Formal Analysis; writing original draft

Sandwell: Software

Hallett: Supervision; Validation; review and editing


Optimization of Mini-Grid Configuration
AC Mini-Grid Applications
Grid-Connected Village with Productive Loads
CO₂

Techno-economic assessment of biomass gasification-based mini-grids for productive energy applications: The case of rural India

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Abstract

As the costs of solar PV continuously decrease and pollution legislation imposes less burning of agricultural residues, decentralized renewable energy is increasingly affordable for providing electricity to one billion people lacking access to a power grid. This paper presents a techno-economic feasibility case study of biomass gasification in off-grid and grid-connected mini-grids for community-scale energy application in rural Uttar Pradesh, India. Energy demand data was collected through surveys in a village with irrigation and agro-processing loads and off-grid households and used to construct a seasonal load profile based on statistical methods. This was used to simulate single-source and hybrid mini-grids based on solar PV, biomass gasification and diesel generation using HOMER Pro. Hybrid PV-biomass or PV-diesel systems were found to offer the highest reliability for off-grid power at the lowest cost. Single-source PV was cheaper than biomass gasification, though the cost of electricity is highly sensitive to biomass supply and gasifier maintenance. Both renewable options were around half the cost of diesel generation. The findings held across grid-connected systems with weak, moderate and strong reliability of grid supply. This suggests that biomass gasification-based mini-grids are not cost-competitive with PV unless the two generation sources are combined in a hybrid system, though they require operational testing prior to implementation.

Keywords

Biomass gasification, solar PV, mini-grid, rural electrification, renewable energy, India

Word count

6442

1. Introduction

1.1 Energy access challenges in India

Many nations in the Global South have no access to reliable power supply. Providing modern energy for the approximately one billion people lacking reliable access to an electricity grid in a sustainable manner is an urgent global priority, as energy is fundamental to improve quality of life and enhance human development [1], [2].

India has historically been home to the largest population without electricity access [3]. Over 90% of those affected are poor or rural populations [4]. Despite expansion of the national electricity network, millions of people remain off-grid. Many areas already connected to the grid suffer from frequent blackouts and poor quality of power supply [5]. Incumbent energy technologies such as diesel generators have high operating costs and low efficiency. Moreover, diesel generators are major emitters of black carbon and greenhouse gases (GHG) and hazardous to human health [6]–[9].

Decentralized renewable energy systems are increasingly viewed as an alternative to grid extension and traditional fuels. In under-electrified zones, small-scale generation systems can rapidly and cost-effectively increase access to quality electricity services while decarbonizing power supply [10].

1.2 Biomass gasification for rural electrification

Biomass gasification is a thermochemical conversion process that converts biomass into a useful energy form known as producer gas. Gasification involves partial combustion of the biomass under limited oxygen supply, generating producer gas composed of the combustible gases H_2, CO and CH_4, as well as CO_2, N_2, tar and ash as by-products [11]. Clean producer gas can be used as a fuel in internal combustion engines to generate electricity.

Biomass power has immense potential in India given its large agrarian economy [12]. Feedstock is abundantly available in multiple forms, including agriculture and forestry residues, agroindustry wastes, and energy crops grown on marginal land [13]. The estimated surplus biomass available is about 120–150 MTpa, corresponding to a potential of ca. 18,000 MW of electrical generation capacity [14].

Small-scale (< 100 kW_e) biomass gasifiers are a promising decentralized technology for rural electrification owing to their low cost, simple construction, local feedstock availability and technology maturity [15]. Biomass gasification-based power generation systems of 3–500 kW_e are commercially available in India [16]. They have been developed and deployed for rural electrification in India since the 1980s [17]–[21]. A number of case studies have reported on operational viability [18]–[22]. However, a significant proportion of these projects have stopped functioning or are defective [20], [23]–[27]. Various limitations that were reported are summarized in Table 1 .

TABLE 1: OVERVIEW OF VARIOUS LIMITATIONS REPORTED FOR BIOMASS GASIFICATION PROJECTS IN THE LITERATURE

Criteria	Limitation

Technical [19],[29],[32],[33]	• Inability of gasifier to handle different feedstocks • Availability of gasifiers only in standard capacities • High maintenance costs for the engine • Inadequate post-installation maintenance • Lack of modularity leading to inability to cope with increasing consumer demand
Operational [26], [34]	• Difficulty in procuring feedstock especially during monsoon season • Limited supply of spare parts locally • Unavailability of skilled manpower • Operational and maintenance procedures not strictly followed
Business [24], [29], [35]	• Asset underutilization (i.e. low plant load factor, defined as the average proportion of power supplied as a fraction of its maximum) • Limited revenue generation from residential users • Long payback times • High risk of investments

Biomass gasification in India has been found to be financially feasible and competitive with grid extension, solar PV and diesel generation [17], [28]–[33]. However, its expansion has been far short of theoretical potential [12]. Due to the requirement for high plant load factor >75% for economic viability [15], planning of biomass rural electrification projects requires comprehensive analysis of demand and resources at a very specific local level [34].

1.3 Mini-grid simulation and optimization

Mini-grids are decentralized energy networks that can integrate a high mix of renewables to provide reliable energy supply to off-grid communities. They typically consist of energy generation from solar PV, biomass gasification, wind or diesel; battery storage; and balance of systems, and can be either off-grid or grid-connected. As mini-grids provide specialized services to a small group of consumers, they usually have higher energy prices compared to the main grid [35].

Diesel generators have been deployed extensively in mini-grids, and are forecasted to remain a vital component in project design for backup [36]. Escalating fuel prices and high emissions from diesel have pushed mini-grid developers to seek to incorporate renewable energy and storage into their mix [37]. Hybrid energy systems, consisting of two or more energy sources for generation of power, have emerged as a possible solution to increase the amount of generation for the same installed capacity, potentially making mini-grids more economically and financially attractive [38]–[40].

1.4 Study overview and aims

Although many works have attempted to design biomass systems for rural electrification in the Global South, these have critical shortfalls from the perspective of real mini-grid operators. There is a need to investigate in closer detail the effect of technical and operating parameters such as the biomass gasifier capital cost (which scales non-linearly with component capacity [41]), maintenance requirements and downtime, and disruptions in feedstock supply which are expected to strongly impact project economics but are frequently neglected in the literature. While most studies have considered purely residential loads, the integration of high-consuming commercial or agricultural (so-called "productive") energy loads such as agro-processing and irrigation is beneficial to increase plant load factor, reduce electricity costs and improve viability of mini-grid projects [42], [43].

This study addresses the need for an up-to-date study of the viability of biomass gasification for rural electrification to meet the real needs of agricultural, commercial and domestic users. India is used as a case study as its rural populations are representative of other nations from the Global South. We compare the economics of biomass with solar PV, diesel, PV-diesel and PV-biomass hybrids for electrification of a village with considerable productive loads. The novelty of this work lies in its use of realistic inputs for techno-economic analysis, namely the latest market prices for equipment, biomass feedstock and fuel [44], [45], and real-time seasonal energy demand data based on surveys of real commercial and agricultural users specific to a location, which is scarcely reported in the literature. We have also compared biomass gasifiers with different maintenance requirements, a key design decision that is frequently overlooked. The objective is to provide a framework to include operational considerations while designing mini-grid systems. The findings apply to least-cost design of mini-grids for provision of affordable, reliable low-carbon electricity supply to 1 billion people globally [46].

Energy demand data was collected from commercial and agricultural energy consumers in a severely under-electrified region in the northern state of Uttar Pradesh, India. Simulations of off-grid and grid-connected mini-grids under weak, medium and strong grid availability were run using HOMER software. The optimal mini-grid for each of five generation configurations were found, based on the levelized cost of electricity (LCOE), supply reliability and GHG emissions. A comparison of technical specifications of two different Indian gasifier suppliers was made considering their respective capital costs, maintenance requirements and downtime. Finally, a multivariate sensitivity test was used to examine how LCOE was affected by changes in biomass price and availability, gasification process parameters and battery lifetime.

2. Methodology

2.1 Profile of the study area

The northern state of Uttar Pradesh is the most populous state in India [47] and contains the largest off-grid and underelectrified population [3], [5]. In eastern Uttar Pradesh lies Bahraich district, with a population of nearly 3.5 million as of 2011, of which 88% reside in rural areas [47]. Although according to the Government's web portal universal household electrification has been achieved [48], it is observed that villages receive fewer than fourteen hours of power supply on a typical day according to live grid monitoring (Prayas Energy Group, 2018 [5]). Eastern Uttar Pradesh has a largely agrarian economy [49], making it a potentially suitable location for biomass power.

2.2 Site and demand assessment

Energy demand data was collected by surveying in the village of Nibiya (Nawabganj block, Nanpara tehsil), Bahraich, Uttar Pradesh, India in June 2018. The village has partial grid connectivity but poor supply of fewer than 8 hours per day as reported by residents, and villagers are reliant on diesel engines for commercial and agricultural power. A village walkthrough was carried out to identify the major electrical loads present (Table 2), which were used to construct a load profile. The village consists of roughly 80 households with limited domestic energy consumption, and whose lighting needs are mainly met by kerosene lamps. The major electrical loads are four irrigation pumps and one rice mill. Their energy consumption patterns were assessed through a primary survey with their owners. The survey consisted of questions about connectivity to the grid or another energy source, diesel fuel consumption, operating hours, devices (i.e. machines or appliances) present, device power ratings, and device time of use during the previous day, using a similar methodology to that reported by Sandwell *et al.* [49]. Information on the seasonal use of each device in each month of the year was also collected. Off-grid households were briefly visited to establish the basic needs of the households, which agreed with the findings of our 2016 study from a nearby location [49]. Survey data from the previous study was used to estimate household electrical energy demand. Details of the time of use and power rating of each device are provided in the electronic supplementary information (ESI, Section S1). The survey findings were validated by comparison with survey data collected from approximately 50 other nearby villages and from the literature [50].

TABLE 2: ASSESSMENT OF MAJOR ENERGY LOADS IN NIBIYA VILLAGE, UTTAR PRADESH.

Load	Quantity	Appliances with AC power rating (where applicable)
Household	80	1 fan (45 W); 2 LED lights (10 W each); 1 mobile charging point (5 W)
Irrigation pump	4	5,000 W
Small mill	1	Rice dehusker (5,650 W); Rice polisher (2,250 W)

2.3 Load profile construction

The energy demand data collected from Nibiya village was used to construct a daily load profile with hourly values, using an open-source modelling tool for simulating load profiles, available at https://github.com/phil-sandwell/Load Simulator. The reader is referred to Sandwell *et al.* [49] for further information on load profile construction.

The Python script produces a user-specified percentile value for the hourly demand profile for each month, which we set to be the 100th percentile to represent the peak load that occurs due to the random variability of users turning appliances on or off at different times. This was used to calculate the time-step variability in HOMER, as described in section 2.5.2.

The average daily load profile obtained using the Load Simulator for each month of the year for Nibiya is shown in Fig. 1. The results of the simulation and time-step variability after adjustment in HOMER are summarized in

Table 3 below. The months of high demand represent months where the rice mill and irrigation pumps are both in operation. During July and August, neither the pumps or mills are in operation due to the monsoon, resulting in low energy demand.

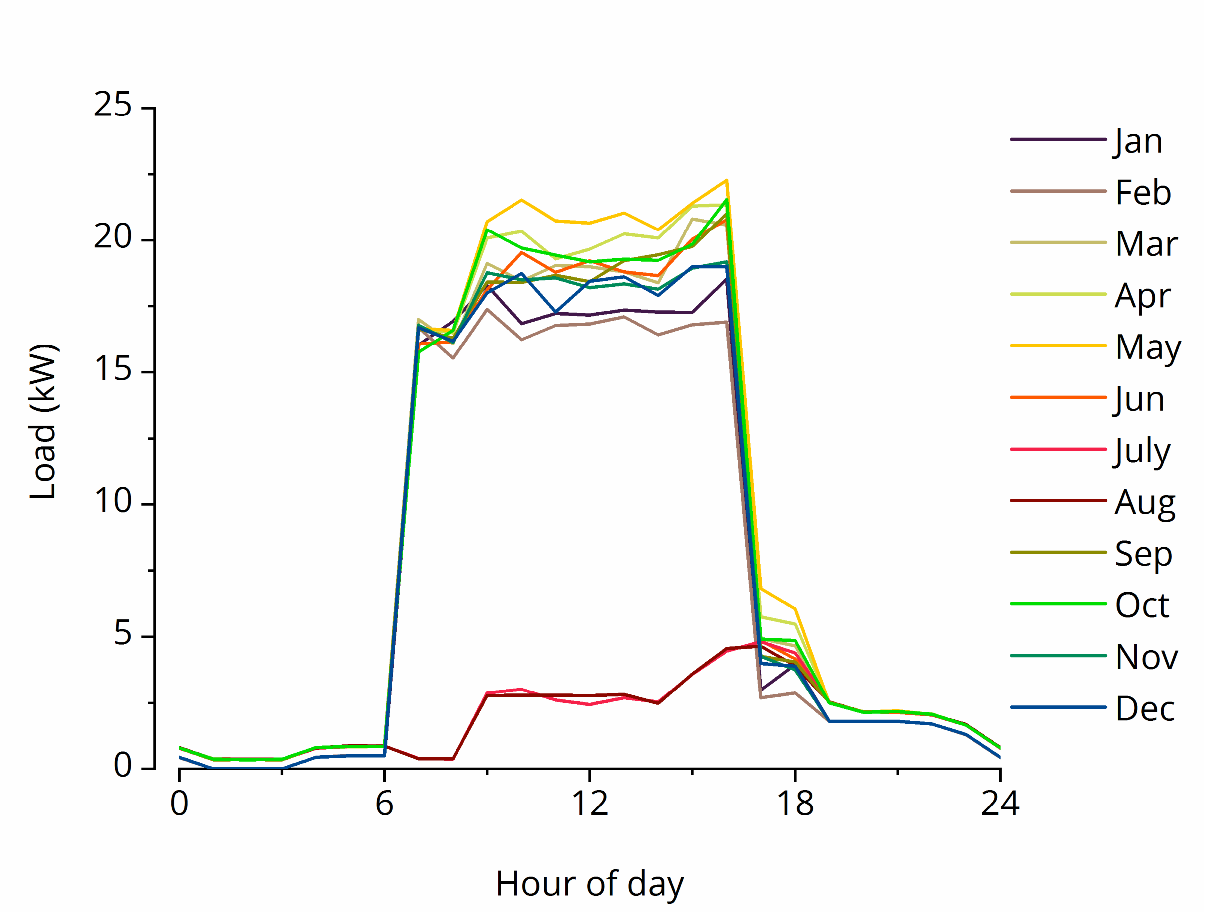


FIG. 1: LOAD PROFILE SHOWING THE DAILY AVERAGE DEMAND FOR NIBIYA VILLAGE, UTTAR PRADESH, INDIA.

TABLE 3: SUMMARY OF RESULTS OF LOAD ESTIMATION (100TH PERCENTILE)

Parameter	Value
Average daily energy demand (kWh/day)	180
Average load (kW)	7.5
Peak load (kW)	30.4
Load factor [a]	0.25
Time-step variability (%)	15.3

[a] The load factor is the ratio of the average load to the peak load.

2.4 HOMER software description

HOMER is a software tool for simulating and optimizing energy systems, including both renewable and conventional sources, in off-grid and grid-connected modes. It enables optimal mini-grid sizing by ranking different generation and storage configurations according to their levelized electricity cost. Major components such as the PV array, biomass, converter, batteries and diesel generator are already modelled within the software. The reason for choosing HOMER for this study over other available options is described in the Table below [48],[62],[63].

TABLE 4: ASSESSING HOMER'S SUITABILITY COMPARED TO OTHER SIMILAR TOOLS AVAILABLE

Tool	Design Optimization	Load profile as time series data	Biomass Gasification model
HOMER	✓	✓	✓
iHOGA	✓	✓	✕
RETScreen	✓	✕	✕
DER-CAM	✓	✕	✕
EnergyPro	✕	✓	✓

2.5 Homer software inputs

2.5.1 Meteorological data

The solar resource used for Bahraich, Uttar Pradesh at a location of 27°34.3′N latitude and 81°35.9′E longitude was taken from the NASA Surface Meteorology and Solar Energy database integrated within HOMER. The annual average solar radiation was 5.36 $kWh/m^2/day$ and the average clearness index was 0.61.

2.5.2 Load profile

The load profile defines the total amount of electrical energy consumption by the system. HOMER takes hourly values of load profile as one of its inputs. The Python simulation described in Section 2.3 was used to provide the load profile. HOMER requires input of both a daily load profile as well as the load variability, adding randomness to the load data to make it more realistic. The time-step variability in HOMER was manually adjusted until the peak load of the resulting load profile matched the 100th percentile run from the Python simulation. This allows for cases of maximal electricity demand to be considered, which is relevant when designing systems with high reliability requirements.

2.5.3 Component characteristics

We consider a mini-grid comprising energy generation (solar PV, biomass, diesel), a battery bank, converters, and a low voltage distribution network. A mature monocrystalline silicon PV technology mounted on fixed stainless-steel structures was considered for this study. The lifetime of the PV panels is taken as 20 years and the derating factor is considered at 80%. The operation of a biomass gasifier and producer gas engine are modelled together using HOMER's biomass module. The major physical properties of a gasifier are the maximum electrical output (in kW_e), lifetime in number of operating hours, and the biomass fuel curve, which gives the relation between quantity of fuel consumed to electrical power produced.

Gasifier capacities were constrained between 15–25 kW$_e$, where kW$_e$ is the maximum electrical output after accounting for ~33% in-plant consumption relative to the rated electrical capacity, kW$_{rated}$. The lifetime of the gasifier is considered as 150,000 hours with regular downtime of 72 hours for maintenance every 2,000 operating hours, based on manufacturer specifications. Other specifications are summarized in the ESI (Section S2). A generic diesel generator with a lifetime of 80,000 hours and the same maintenance parameters as the gasifier was modelled. We employ generic valve-regulated lead acid battery technology as the technology is mature, low-cost and widely deployed in India [51]. Batteries are considered to have a lifetime of 5 years, typical of actual ground conditions in rural India [52] and a throughput of 7,500 kWh for 300 life cycles at 30% depth of discharge. The converter (combined inverter and rectifier) was assumed to have a lifetime of 15 years and efficiency of 95%. A low-voltage distribution network spanning approx. 3 km was considered [53]. Optional interconnectivity to the national grid network was assumed, though no additional components were considered necessary for a grid-connected mini-grid. The prices of fuel and components are discussed in the next section.

2.5.4 Economic and emissions data

The capital costs and operations and maintenance (O&M) costs of all components are presented in Table 5. Component capital costs were taken either from recent literature sources or directly from supplier websites such as Indiamart and include local taxes and transport. Biomass gasifier component costs were obtained directly from two local suppliers, known as Supplier A (Karnataka, India) and Supplier B (Bihar, India). The biomass price was considered as 4 INR/kg (0.058 USD/kg) over the entire project duration [54]. For all components with lifetime of less than 20 years, the replacement cost was assumed to be 80% of the original capital cost. Fixed capital costs for the system were taken as INR 1,000,000 (USD 14,543) which includes the distribution network, distribution boxes and civil works; fixed operating costs were considered as INR 50,000 (USD 727) per year excluding salaries [53], [54]. The net CO$_2$-equivalent (CO$_2$e) emissions of electricity generated from various sources used to perform emissions savings calculations are also presented. In the case of biomass gasification, the net CO$_2$e emission does not consider the CO$_2$ emitted during producer gas combustion as biomass is renewable. The GHG emissions value for diesel generation assumes complete combustion of the carbon fraction in diesel fuel [55].

TABLE 5: COST AND EMISSIONS DATA FOR MAJOR MINI-GRID GENERATION, STORAGE AND DISTRIBUTION COMPONENTS. FULL ECONOMIC AND TECHNICAL SPECIFICATIONS CAN BE FOUND IN THE ESI.

Parameter	Capital or fuel cost	Annual O&M cost	Emissions
Solar PV	50,000 INR/kW$_p$ (727 $/kWp*) [53] [a]	2% of capital cost [56]	0.05 kgCO$_2$e/kWh [57] [b]
Biomass	147,000–250,000 [c] INR/kW (2138 - 3636 $/kW)	5,250 INR/kW (76 $/kW)	0.09 kgCO$_2$e/kWh [58]
Diesel generator	12,000 INR/kW (175	10% of capital cost [15]	-

	$/kW) [53]		
Diesel fuel	70 INR/liter (1.02 $/liter) [59]	-	2.68 kgCO_2e/liter [55]
Converter [d]	50,000 INR/kW (727 $/kW) [60]	10% of capital cost [15]	-
Battery	10,000 INR/kWh (145 $/kWh) [61]	1% of capital cost	25.2 kgCO_2e/kWh capacity over 5 year lifetime [62]
Fixed costs	1,000,000 INR ($ 14543) [54]	5% of capital cost [54]	-
National grid (Uttar Pradesh)	-	-	1.05 kgCO_2e/kWh [63]

[a] PV costs include the cost of mounting structures, inverter and charge controller per kW_p.

[b] All electricity generated by solar PV, including excess generation which is not used or stored by the system, is considered in the calculations for compatibility with the literature value.

[c] For Gasifier A, capital costs include gasifier and gas engine and have been calculated based on costs of 250,000 INR/kW_e for a system of 17 kW_e and 147,000 INR/kW_e for a system of 48 kW_e provided by Supplier A based in Karnataka, India.

[d] Converter costs provided per kW include only the rectifier (DC to AC) as the inverter (AC to DC) is already included in the PV costs.

* 1 USD = 68.76 INR when this study was carried out (July 2018) and the same conversion rate is used throughout this paper

2.6 Modelling and optimization of mini-grid configurations

Modelling of mini-grids was carried out using HOMER. For this study, five different mini-grid configurations were considered, namely solar PV, biomass gasification, diesel, solar-biomass and solar-diesel generation. These were compared in both off-grid and grid-connected modes. The same load profile constructed from survey data representing Nibiya village was used for all mini-grid configurations. The simulation settings were for a period of 20 years, an inflation rate of 4.65% [64], and a discount rate of 6.25% [65]. The optimizer settings were as follows: 8,760 timesteps of one hour each; 20,000 simulations per optimization; system design and NPC precision of 0.001, and focus factor of 2.

The optimal off-grid and grid-connected mini-grid configurations were identified as those having the lowest levelized cost of electricity (LCOE) as calculated by HOMER in INR/kWh. Details of the modelling and optimization methodology can be found in the ESI (Section S3).

For grid-connected mini-grids different hypothetical grid scenarios were considered, namely a weak, moderate and strong grid, characterized by increasing availability and reliability of power supply. Grid availability data was obtained from representative sites for real grid-connected locations monitored by Prayas Energy Group [5]. A snapshot of the grid availability in the hottest month when supply is generally worst (May) and in the middle of winter when it is typically most reliable (January) is provided in Table 6. The grid reliability scenarios have been plotted visually in the ESI (Section S4).

TABLE 6: COMPARISON OF THREE TYPES OF GRID AVAILABILITY, REPORTED AS AVERAGE UPTIME OVER A GIVEN CALENDAR MONTH BASED ON HISTORIC DATA [5].

Grid type	Availability in January 2018	Availability in May 2018
Weak	42.9%	2.8%
Moderate	71.7%	62.9%
Strong	94.6%	62.5%

The CO_2e emissions from all size-optimized mini-grids were compared against a size-optimized off-grid diesel mini-grid to assess their environmental impact. Diesel generators are commonly used in rural India as backup power or to cover daily loads [36], representing a realistic baseline case against which to compare renewable or hybrid mini-grid emissions. Emission factors for all major mini-grid components are reported in Table 5.

2.7 Sensitivity analysis

A multivariate sensitivity analysis was performed in HOMER, which was essential as some parameters are linked to each other. For instance, if the availability of biomass is low, the price of biomass feedstock is likely to increase. Six major uncertain technical parameters were identified and the base case was characterized as follows:

- Battery life: 5 years
- Price of biomass feedstock: 4 INR/kg (0.058 USD/kg)
- Biomass availability: 0.385 tons/day
- Gasification ratio: 2.5 kg producer gas/kg biomass
- Fuel curve slope: 3.45 kg producer gas/h/kW_{output}
- Fuel curve intercept coefficient: 0.4 kg producer gas/h/kW_{rated}

The biomass availability was chosen by trial and error in HOMER, such that barely adequate biomass was available for a standalone biomass mini-grid to operate. If excess biomass was considered, negligible sensitivity to change in the above-mentioned parameters was observed. Four uncertain scenarios were considered for analysis in which each parameter was set at ±5% and ±15%.

2.8 Gasifier comparison

Maintenance requirements of biomass gasifiers vary considerably according to the gasifier design, but cannot be investigated using HOMER's sensitivity analysis function. Simulations were thus carried out by considering different values of (1) the number of hours of continuous operation after which maintenance is required, and (2) the hours of downtime during each maintenance event. Four different scenarios were considered, taking either 1500 or 2500 hours of continuous operation followed by either 48 or 120 hours of downtime.

A comparison was also made between two gasifier manufacturers with different technical and operating specifications. Both gasifiers are commercial downdraft models available in India. Gasifier A is a semi-automated gasifier with numerous safety features which is more feedstock-flexible and has a higher capital cost but requires less maintenance. Gasifier B is a cheaper gasifier with more maintenance requirements as is more sensitive to fuel quality. An overview of the two gasifiers is provided in Table 7. The analysis was carried out by considering different operational hours and maintenance downtime for these systems, for the same load. A comparison of the LCOE was made for both standalone (Bio) and hybrid (PV–Bio) configurations.

TABLE 7. OVERVIEW OF TECHNICAL, ECONOMIC AND OPERATIONAL SPECIFICATIONS OF TWO DIFFERENT GASIFIER TYPES FROM DIFFERENT INDIAN SUPPLIERS.

Gasifier type	**Gasifier A**	**Gasifier B**
Capital cost [a]	168,000–250,000 INR/kW (2443-3636 $/KW)	92,000 INR/kW (1338 $/kW)
Replacement cost	80% of capital cost	80% of capital cost
O&M cost	5,250 INR/kW/year (i.e. 0.6 INR/kW/h) (76 $/kW/year)	7,000 INR/kW/year (i.e. 0.8 INR/kW/h) (102 $/kW/year)
Minimum load ratio (%)	30	30
Lifetime (hours)	150,000	150,000
Minimum runtime (h)	480	30
Gasification ratio (kg gas/kg biomass)	2.5	3
Fuel curve slope (kg gas/h/kW$_{output}$)	3.45	3.3
Fuel curve intercept (kg gas/h/kW$_{rated}$)	0.4	0.6

[a] For Gasifier A, capital costs include gasifier and gas engine and have been calculated based on costs of 250,000 INR/kW$_e$ for a system of 17 kW$_e$ and 147,000 INR/kW$_e$ for a system of 48 kW$_e$ provided by Supplier A based in Karnataka, India. For Gasifier B, capital costs include gasifier and gas engine and have been calculated based on a cost provided of 92,000 INR/kW for a 25 kW$_e$ system. Costs were provided by Supplier B based in Bihar, India.

3. Results and Discussion

3.1 Techno-economic analysis of mini-grid configurations

Simulations of different AC mini-grid systems were carried out using HOMER. All mini-grids modelled considered energy generation, battery storage, converters and a low-voltage distribution network. The load to be served was a rural village in Bahraich district, Uttar Pradesh, India containing 80 households, 4 irrigation pumps and a rice mill. HOMER simulations were carried out for one year of operations and the costs extrapolated to 20 years. An identical load profile with average requirement of 180 kWh/day and an average peak load of 30.4 kW was used to model all configurations.

3.1.1 *Off-grid mini-grids*

First, the LCOE of five mini-grid configurations was compared in off-grid mode. Simulations were carried out using an annual capacity shortage constraint set to between 0 to 10% to obtain the configuration with the lowest LCOE. The capacity shortage constraint represents the maximum allowable shortfall of energy generation divided by total electric load annually; it was assumed that users would not accept lower reliability level than 90% [66]. Fig. 2 shows the variation of LCOE with annual capacity shortage for all mini-grid configurations considered.

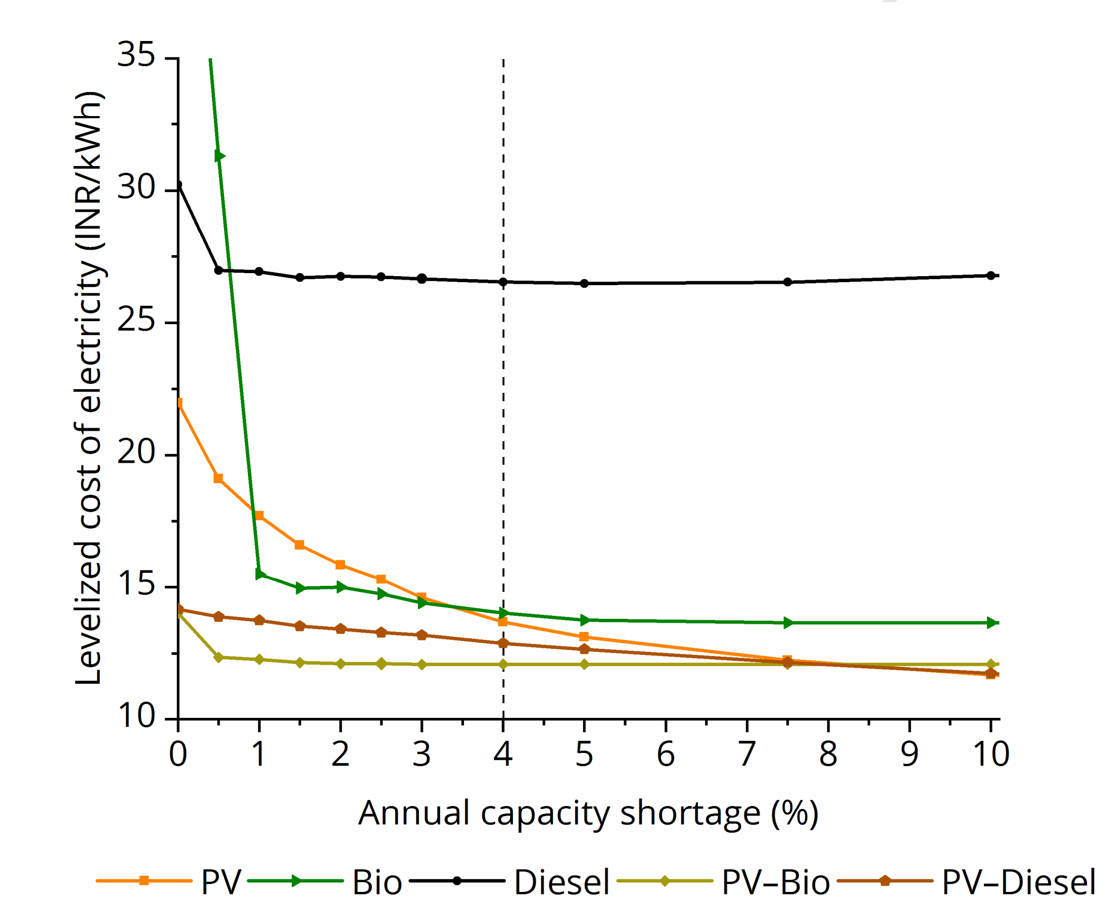


FIG. 2: EFFECT OF CAPACITY SHORTAGE ON THE LEVELIZED COST OF ELECTRICITY FOR OPTIMAL CONFIGURATIONS FOR OFF-GRID SOLAR PHOTOVOLTAIC, BIOMASS, DIESEL, SOLAR–BIOMASS AND SOLAR–DIESEL MINI-GRIDS.

Fig. 2 shows that as the energy shortfall approaches zero, the LCOE increases sharply for standalone mini-grids, agreeing with previous works [67], [68]. The increase in LCOE is most significant for biomass and PV below 4% capacity shortage, as they require higher battery storage capacity to meet high reliability constraints leading to high costs. This is especially apparent for a standalone biomass system, leading to a significantly oversized gasifier and battery bank in order to achieve near 0% energy shortfall. In contrast, diesel mini-grids show an almost constant price, other than at high reliability, as observed by Sandwell *et al.* [68]. This is as expected for an asset for which energy generation and costs are very closely linked.

Biomass gasification is the lowest-LCOE option amongst single generation sources for capacity shortage between 1–3%. This is attributed to the fact that solar power is intermittent, requiring a relatively large battery bank for backup compared to biomass. In this range, the maintenance times of biomass gasification can be accommodated and hence it is cheaper than solar. However, at very low capacity shortage of 1% or less, biomass gasification becomes more expensive than even diesel generation. This is linked to the gasifier maintenance requirements, which are compensated for by oversizing the gasifier and battery bank, resulting in low capacity utilization and excessive capital costs.

The marginal cost of higher reliability is greatest for annual capacity shortage of 4% or less. If greater than 4% blackout is permissible, the marginal difference in LCOE for all standalone systems is relatively lower. In the case of hybrid systems, the threshold reliability level is around 1%. Considering PV, the additional cost of providing more reliable service can be reduced by using a biomass gasifier or diesel generator to provide backup power in lieu of a larger battery bank. This agrees with previous findings that hybrid mini-grids can potentially provide much more reliable service at a lower cost [31], [69]. Hybrid mini-grids show more linear behavior in response to varying reliability as witnessed by others [68]. PV–Bio is cheaper than PV–Diesel when very high reliability is required, as the system relies heavily on Bio or Diesel for backup power which incurs higher costs for the diesel system.

In subsequent parts of this study, the annual capacity shortage was set at 4% for all mini-grid configurations. At this reliability level, the LCOE for solar, biomass and diesel were 13.7, 14.2 and 26.5 INR/kWh respectively. The LCOE for standalone Bio lies in the range reported by Buragohain *et al.* [15] of 13.5–15 INR/kWh dependent on the plant load factor. Cost declines in PV of nearly 40% have been witnessed in recent years [44], which has resulted in PV becoming the lowest-LCOE option at 13.7 INR/kWh. Further capital cost decreases are expected for solar PV with ongoing research, while diesel fuel prices are expected to rise due to high volatility and recent deregulation [70].

These LCOE values represent *minimum* tariffs to recover unsubsidized capital costs and operating costs. As expected, all LCOE values found are significantly higher than the subsidized grid tariff in Uttar Pradesh of 5 INR/kWh [71]. Mini-grid tariffs higher than grid tariffs do not preclude consumer willingness to pay for electricity, provided that, service reliability can be offered [72]. Cost-competitiveness with incumbent diesel generation is more critical. All renewable mini-grid options evaluated offered an LCOE around half the price of diesel generation (INR 26/kWh). These optimal configurations are examined in more detail in Table 8.

TABLE 8: COMPARISON BETWEEN OPTIMAL OFF-GRID MINI-GRID CONFIGURATIONS AT 4% ANNUAL CAPACITY SHORTAGE.

	LCOE (INR/kWh*)	Energy generated (kWh/year)	% PV penetration [a]	Diesel use (liters/year)	CO_2e emissions (ktCO_2e/year)	Emissions saved (% rel. to diesel)
PV	13.7 (0.20)	147,765	100	-	6.2	89

Bio	14.2 (0.21)	66,453	-	-	7.9	87
Diesel	26.5 (0.39)	67,712	-	21,772	58.6	0
PV–Bio	12.6 (0.18)	72,300	44.3	-	5.5	91
PV–Diesel	13.6 (0.20)	109,493	96.3	2,158	10.7	82

[a] Defined as the percentage of energy generated from PV as a proportion of the total energy generated by the system.

*The LCOE in USD/kWh is provided in brackets alongside the LCOE in INR/kWh.

From Table 8, it was observed that systems with high PV penetration (i.e. PV and PV–Diesel), a large amount of excess electricity was generated, with ca. 110,000–150,000 kWh/year generated respectively, compared to the need of 65,700 kWh/year. In off-grid systems, the excess electrical power not directly consumed or stored cannot be sold. In the advent of feed-in tariffs for grid-connected mini-grids, the export and sales of electricity to the national grid would improve project economics.

To better understand the reality of a mini-grid supplying power with 4% capacity shortage from the consumer and operator perspective, the timings at which insufficient power is available were examined. The unmet load occurring in a simulated year of operations was obtained from HOMER for optimized mini-grid configurations reported in Table . The blackout timings are presented in Fig. 3.

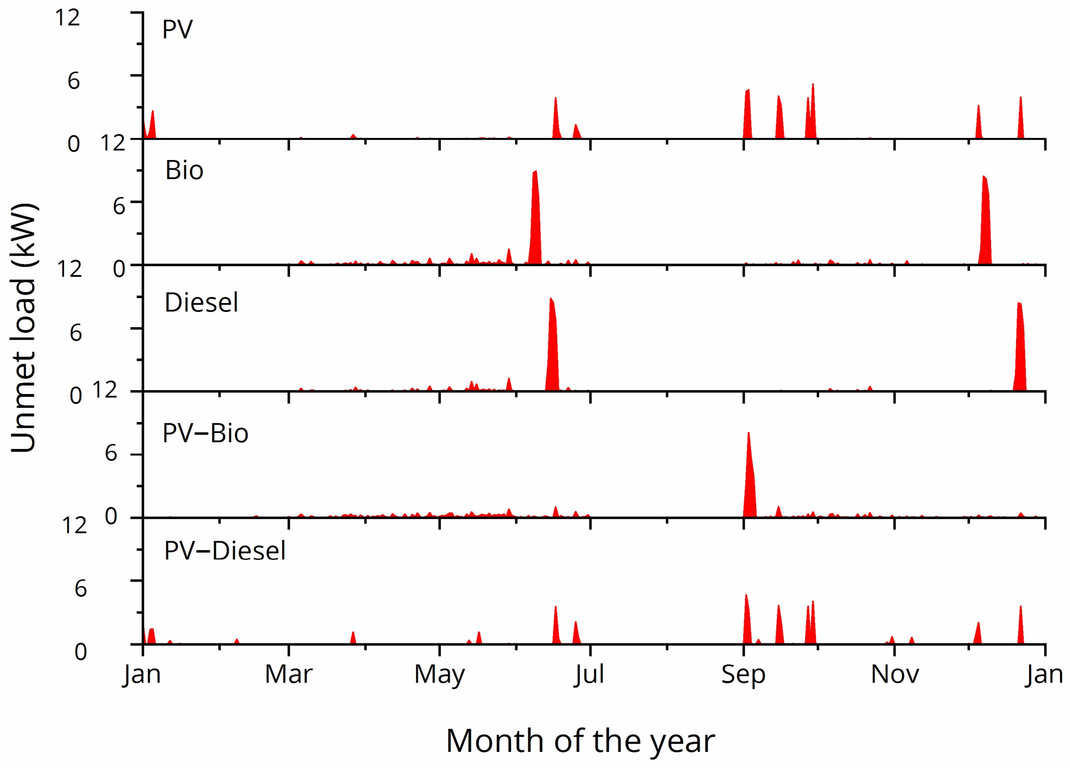


FIG. 3: UNMET LOAD FOR PV, BIOMASS, DIESEL, PV–BIO AND PV–DIESEL MINI-GRIDS AT 4% ANNUAL CAPACITY SHORTAGE.

Fig. 3 shows that biomass gasification and diesel generation show similar energy shortage patterns, with two main peaks of unmet load representing scheduled maintenance. For PV, several peaks of lower magnitude are observed, reflecting seasonal power shortages in the early and late monsoon when demand from irrigation and agro-processing loads is high (June and September) and winter weather experiencing lower solar radiation (December–January). The blackout profile for the PV–Diesel mini-grid is similar to standalone PV, as the hybrid system is mostly supplied by PV generation. However, the magnitude of the unmet load was slightly lower during each blackout event. For PV–Bio, only one major blackout period was observed.

From a consumer perspective, PV and PV–Diesel mini-grids offer the least convenient option, with frequent occurrences of minor blackouts. PV–Bio seems to offer the best performance with only one major blackout. However, the acceptability by the consumer depends on their level of awareness and understanding about the downtime needed for maintenance, whether maintenance times can be scheduled to coincide with periods of low demand, and whether non-essential loads can be shifted around expected downtime.

3.1.2 Grid-connected mini-grids

Next, the effect of the presence of the national grid on mini-grid economics was investigated. This is crucial because of the Government of India's ambitious drive towards national grid extension, meaning that mini-grids are increasingly likely to be built in areas with existing grid connectivity. Rather than being competing power sources, consumers can exploit dual mini-grid and grid connections to benefit from the high service reliability of mini-grids combined with low national grid tariffs. Grid electricity can either be consumed directly (no battery charging) or used to charge the battery bank to reduce the generation capacity needed (battery charging). Scenarios where excess electricity generated by the mini-grid is sold back to the national grid were not considered here.

Grid availability was modelled as weak, moderate or strong. These scenarios are respectively characterized by 10, 17 and 23 hours of power supply per day in winter months, and 0.6, 15 and 15 hours in summer. The LCOE results for cost-optimized mini-grids obtained from HOMER simulations are presented in Table 9.

TABLE 9: THE EFFECT OF MINI-GRID–NATIONAL GRID INTERCONNECTIVITY ON THE LEVELIZED COST OF ELECTRICITY (IN $/KWH IN BRACKETS) AT 4% ANNUAL CAPACITY SHORTAGE.

Grid-type	**No grid**	**Weak grid**		**Moderate grid**		**Strong grid**	
		No battery charging	**With battery charging**	**No battery charging**	**With battery charging**	**No battery charging**	**With battery charging**
PV	13.7 (0.20)	12.2 (0.18)	12 (0.17)	10.9 (0.16)	10 (0.15)	9.4 (0.14)	9 (0.13)
Bio	14.2 (0.21)	12.9 (0.19)	12.8 (0.19)	11.2 (0.16)	11.1 (0.16)	10 (0.15)	10 (0.15)
Diesel	26.5	22.5	22.2	15.2	14.8	11.6	11.5

	(0.39)	(0.33)	(0.32)	(0.22)	(0.22)	(0.17)	(0.17)
PV–Bio	12.6	11.3	11.3	10.3	10.2	9.8	9.6
	(0.18)	(0.16)	(0.16)	(0.15)	(0.15)	(0.14)	(0.14)
PV–Diesel	13.6	12.1	12.1	10.7	10	9.5	9
	(0.20)	(0.18)	(0.18)	(0.16)	(0.15)	(0.14)	(0.13)

Moving from off-grid mini-grids to those with greater grid penetration, system LCOE decreases progressively as the grid supply improves. This reflects the increasing proportion of consumer demand that is met by cheaper national grid electricity, causing the overall LCOE to decrease by up to 30% for the same level of service for renewable mini-grids. The greatest reduction of LCOE of up to 50% was observed for Diesel mini-grids owing to the greater cost differential. This represents the prevalent practice in rural India of using diesel generation to complement the grid in weak-grid areas. However, in both off-grid and grid-connected scenarios, diesel mini-grids were always more expensive than renewable energy based mini-grids on an LCOE basis. Among standalone mini-grids, PV yielded the lowest LCOE; this cost advantage was maintained across all grid supply scenarios. Interestingly, there appears to be a rational argument for developing solar PV mini-grids in grid-connected areas with good supply, as the grid acts as a cheap backup when solar power is unavailable to reduce battery storage requirements. In reality the grid situation in rural areas of northern and eastern India is most accurately represented by a weak grid [5], where PV–Bio followed closely by PV and PV–Diesel mini-grids were most economical.

3.2 Greenhouse gas emissions savings

The potential emissions mitigation for each mini-grid configuration was assessed by calculating the annual CO_2e emissions saved compared to an off-grid diesel mini-grid. The latter was calculated to emit 58.6 ktCO_2e/year, based on 21,772 liters of diesel fuel consumed annually. The percentage GHG emissions savings for various off-grid and grid-connected (weak grid without battery charging) mini-grids relative to the standalone Diesel case are presented in Fig. 4.

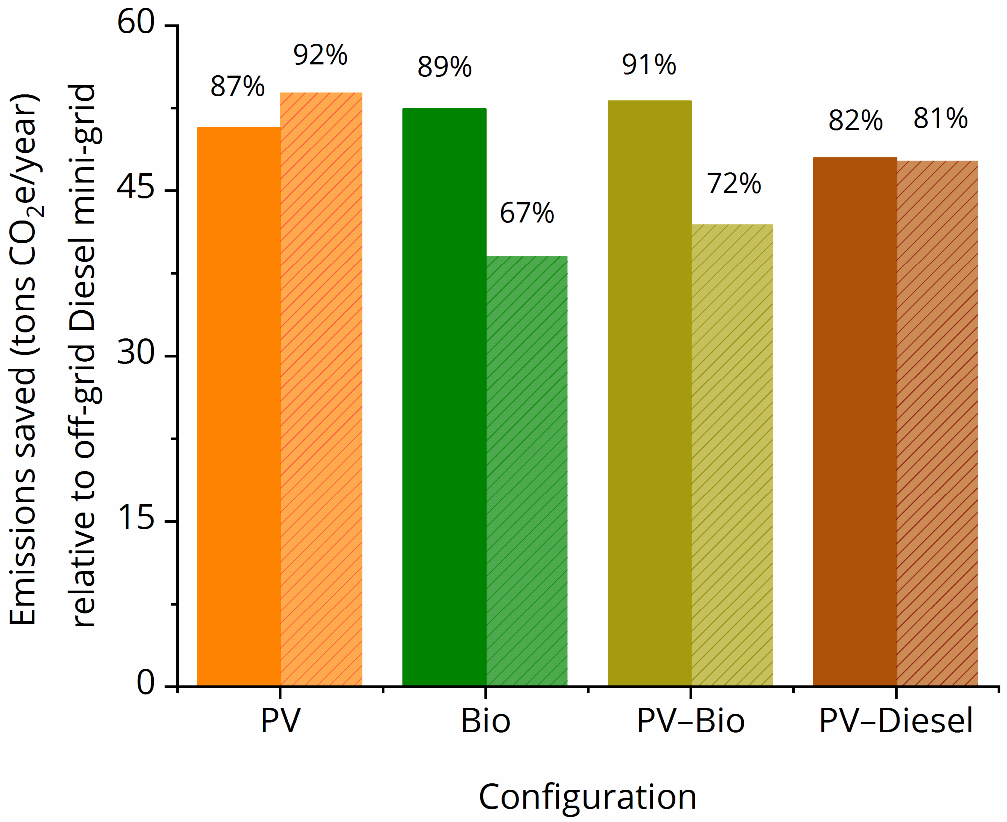


FIG. 4: ANNUAL ABSOLUTE GHG EMISSIONS SAVINGS FOR VARIOUS MINI-GRID CONFIGURATIONS COMPARED TO OFF-GRID DIESEL MINI-GRID AT 4% ANNUAL CAPACITY SHORTAGE. VALUES INSET INDICATE PERCENTAGE SAVINGS RELATIVE TO DIESEL AS ABOVE. SOLID BARS (LEFT SIDE) REPRESENT OFF-GRID MINI-GRIDS AND PATTERNED BARS (RIGHT SIDE) REPRESENT GRID-CONNECTED MINI-GRIDS.

For off-grid systems, all configurations offered large savings in GHG emissions of between 82–91% compared to an off-grid Diesel mini-grid with the same level of service. The emissions from PV are due to considerable GHGs embedded in their manufacture and are comparable to emissions savings from standalone biomass generation. However, GHG savings for grid-connected Bio and PV–Bio are reduced to 67% and 72%, respectively, owing to reliance on carbon-intensive grid supply, whereas savings for PV-dominated systems remain high. These calculations do not take into account the GHG emissions from contingency usage of fossil fuels such as kerosene lamps during power shortages or blackouts. Based on our analysis, PV-based systems and standalone off-grid Bio are the lower-GHG option overall.

3.3 Sensitivity analysis

3.3.1 Multivariate sensitivity analysis

A multivariate sensitivity analysis was carried out to assess the effect of five uncertain parameters on the mini-grid economics – battery lifetime, biomass feedstock cost, biomass feedstock availability, gasification ratio (GR), and biomass requirements of the gasifier. This sensitivity analysis was carried out assuming 4% annual capacity shortage. The results are shown in Fig. 5 below for standalone Bio and for PV–Bio mini-grids in both off-grid and grid-connected modes.

For a Bio system, the LCOE is extremely sensitive to the biomass price, gasification ratio and biomass required by the system. These impact the sufficiency of producer gas to run the generator in the absence of which a bigger battery bank is required for backup, pushing up the LCOE. Biomass supply disruptions are very likely to occur in practice, as agricultural residues and woody biomass feedstocks have complex informal supply chains and seasonal availability [73]. This illustrates the need for more field testing of biomass gasification-based mini-grids as these challenges may lead to escalating operating costs or decreasing service levels and eventual project shutdown.

The LCOE and its sensitivity to uncertainty parameters was seen to reduce as the number of available power generation sources was increased. If one generation source is affected, another can set in to mitigate the effect, reducing the requirement for oversizing the gasifier or battery bank. Greater sensitivity was observed for a biomass gasification system connected to a weak grid than for off-grid PV–Bio systems. This may be because the component sizes are smaller and the system becomes less reliant on the biomass gasifier with the availability of PV. At 4% capacity shortage, a grid-connected hybrid system PV–Bio provided both the lowest LCOE and greatest security of power supply in the event of a disruption in biomass feedstock supply.

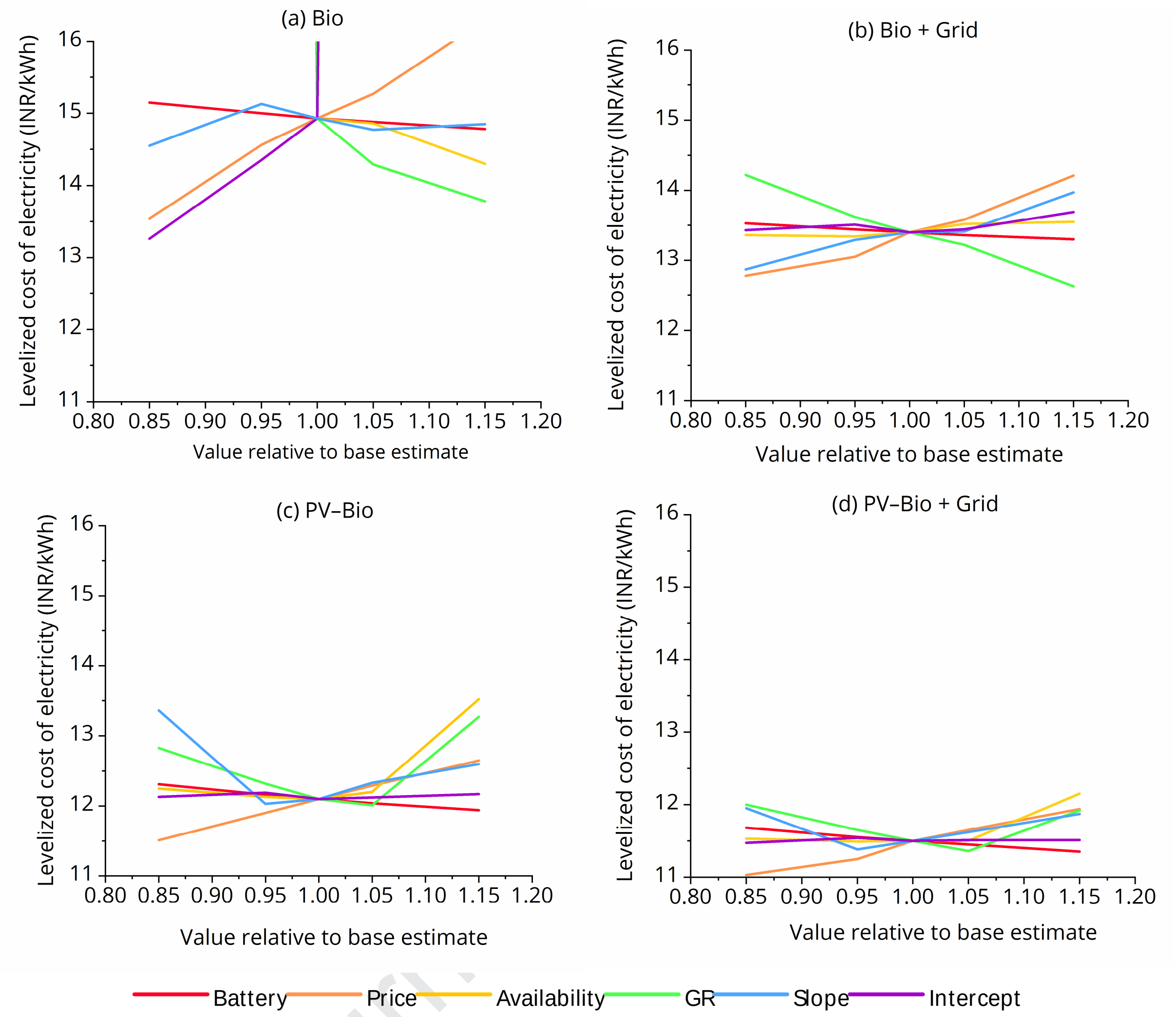


FIG. 5: MULTIVARIATE SENSITIVITY ANALYSIS FOR (A) BIO, (B) BIO + GRID, (C) PV–BIO, AND (D) PV–BIO + GRID SYSTEM CONFIGURATIONS. BASE CASE: BATTERY LIFETIME: 5 YEARS; BIOMASS FEEDSTOCK COST: 4 INR/KG (0.058 USD/KG); GASIFICATION RATIO: 2.5 KG PRODUCER GAS/KG BIOMASS; FUEL CURVE SLOPE: 3.45 KG PRODUCER GAS/H/KW OUTPUT; FUEL CURVE INTERCEPTION COEFFICIENT: 0.4 KG PRODUCER GAS/H/KWRATED; BIOMASS AVAILABILITY: 0.385 TONS/DAY.

3.3.2 Effect of maintenance time

A sensitivity analysis was carried out to study the effect of gasifier maintenance requirements on biomass-based mini-grids. Four different cases (1500 and 2500 running hours of continuous operation, followed by either 48 or 120 hours of downtime) were considered based on manufacturer recommendations. The gasifier capital costs remained the same (Gasifier A). The resulting LCOE for standalone Bio and PV–Bio, in both off-grid and weak-grid connected modes, was plotted against annual capacity shortage in Fig. 6. The LCOE values ranged considerably, so the reader should pay careful attention to the y-axes scaling.

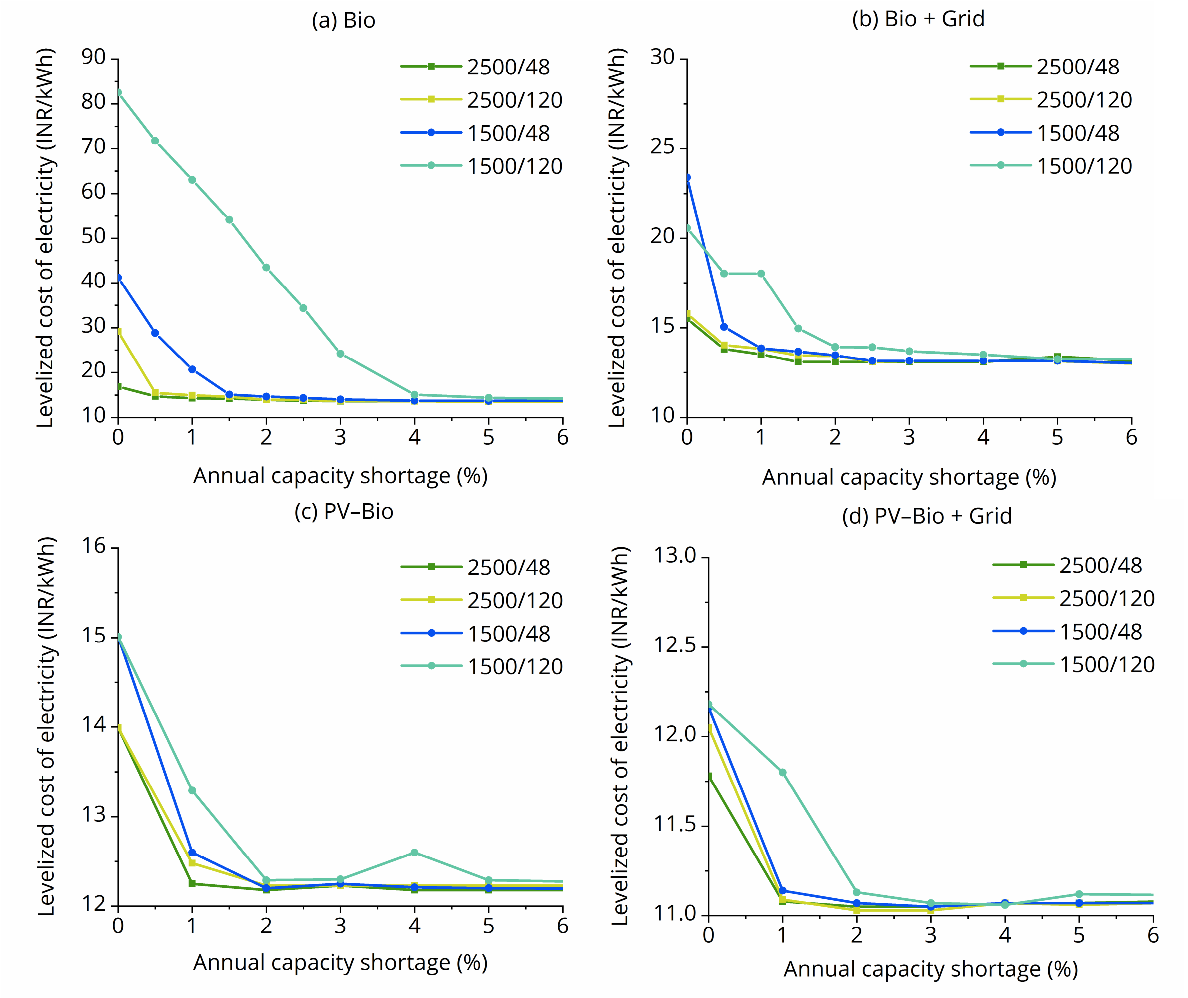


FIG. 6: EFFECT OF MAINTENANCE TIME ON (A) BIO, (B) BIO + GRID, (C) PV–BIO, AND (D) PV–BIO + GRID. THE MAINTENANCE TIMES ARE DENOTED AS *CONTINUOUS RUNNING HOURS/DOWNTIME*, FOR INSTANCE 2500 HOURS OF OPERATION WITH 48 HOURS DOWNTIME IS DENOTED AS *2500/48*.

From Fig. 6, the economics of biomass gasification-based mini-grids are very sensitive to maintenance time. As the continuous running hours were reduced and the downtime increased, the LCOE increased significantly, an effect that was strongest for standalone Bio systems (Fig. 6a) at high reliability. Energy shortfall in these systems arises from multiple long periods of maintenance, which becomes a significant part of (or greater than) the permitted shortfall. In practice, maintenance could be scheduled to coincide with periods of low demand to avoid the need for a costly oversized battery bank. For hybrid systems, in the absence of power supply from PV or the grid, gasifier downtime for maintenance must be compensated by a larger battery bank, which increases the LCOE though to a much less significant degree than for standalone systems. Systems with 2500 hours of continuous operation were consistently cheaper than those with only 1500 hours. This signifies that a gasification system requiring more frequent maintenance is subject to much higher LCOE if the operator is to offer a reliable service. Again, the availability of a larger number of power generation sources reduced the cost for the same level of reliability.

3.3.3 Comparison of gasifier manufacturers

Two gasifier models with different capital costs and technical and operating parameters were compared. Gasifier A is a semi-automated model with higher capital cost but lower maintenance requirements, while Gasifier B is cheaper but has higher operating costs associated with feedstock and maintenance requirements. Both gasifiers were assumed to be paired with the same producer gas engine for electricity generation.

The effect of annual capacity shortage on the LCOE was examined in Fig. 7 for both standalone Bio and hybrid PV–Bio mini-grid configurations.

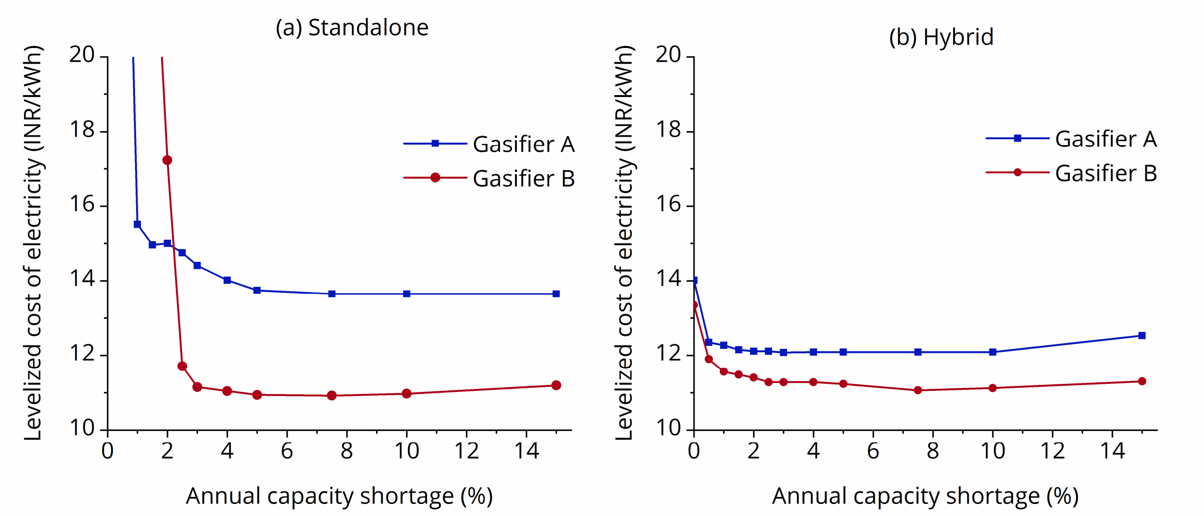


Fig. 7: Comparison between two gasifiers in (a) standalone Bio and (b) hybrid PV–Bio mode.

For a standalone system (Fig. 7a), it can be observed that Gasifier A is cheaper on an LCOE basis than Gasifier B when high reliability (less than 2% shortfall) is required. Where the number of hours of operation required is high, Gasifier A offers lower LCOE as it has lower running costs. For both Gasifier A and B, LCOE increases sharply to reach 50 and 55 INR/kWh for 0% energy shortfall, respectively. At low capacity shortage the maintenance-intensive Gasifier B becomes less cost-effective as long periods of downtime must be compensated by a large battery bank, increasing costs. If service reliability is paramount, it is recommended to invest in a more robust gasification system requiring less maintenance. If annual capacity shortage greater than 2% is permissible, Gasifier B offers significant cost savings at ~11 INR/kWh compared to Gasifier A at ~13.5 INR/kWh.

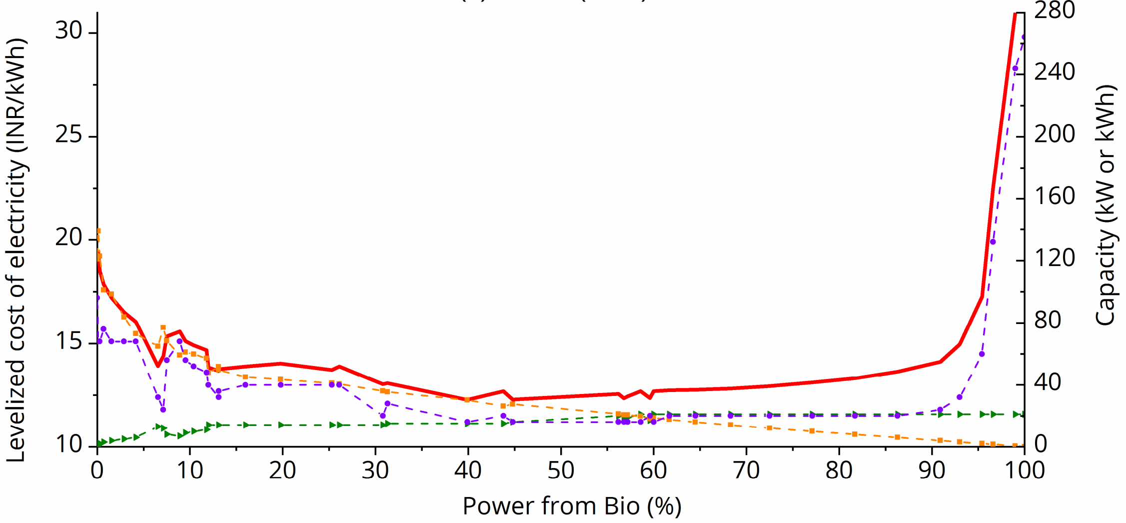
For hybrid PV–Bio systems (Fig. 7b), as seen earlier, most of the generation is from PV and so the sensitivity to fuel requirements and maintenance times is reduced. As a result, the most significant contribution to the LCOE is the capital investment for building the gasifier. Hence, the cheaper Gasifier B always provides cheaper electricity than Gasifier A.

This comparison of gasifier manufacturers does not take into the account the ground realities of operating and maintaining biomass gasifiers in rural India. Our analysis assumes that gasifier and engine servicing are provided on-time, feedstock requirements are always met, and skilled manpower is readily available. Reports from real-life projects indicate that these practical difficulties escalate costs, delay project delivery and reduce profitability of the projects significantly [22], [73]–[75]. This makes hybrid projects significantly more risky than standalone projects and highlights the needs for further on-ground testing.

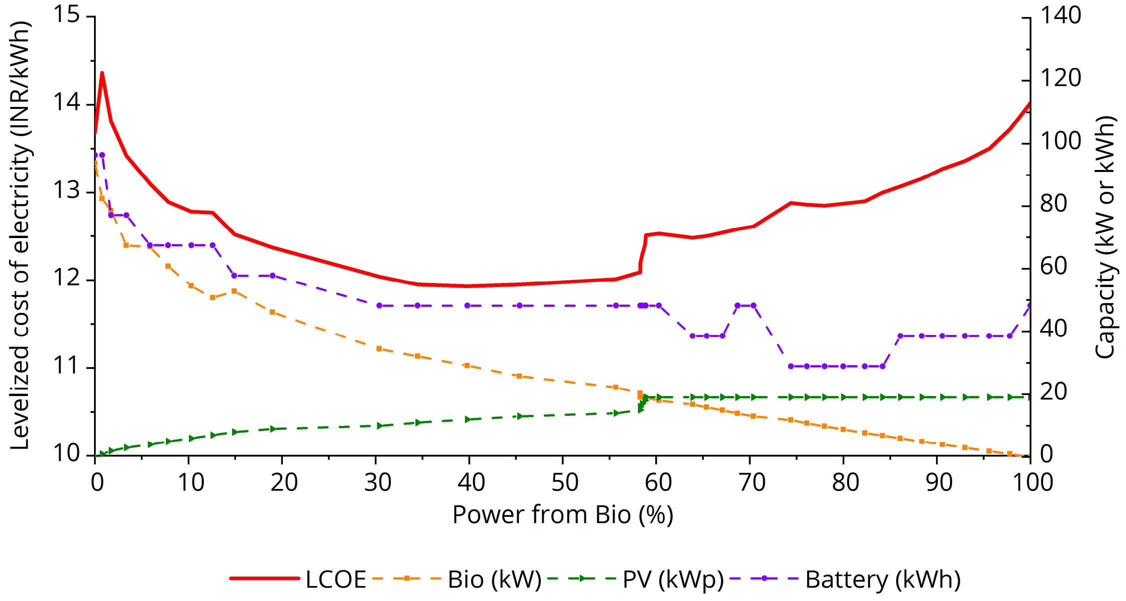
3.4 Trade-offs involved in design of hybrid mini-grids

The findings in sections 3.1–3.3 have shown that hybrid systems appear to be more economical and resilient to uncertainty in technical and operating parameters than standalone systems. In this section, the trade-offs between service reliability, cost and generation sources were examined for designing hybrid PV–Bio mini-grid systems. Two annual capacity shortage cases of 0.5% and 4% were compared and the mix of solar PV and biomass capacity was varied. While very small PV modules are available on the market, the smallest capacity of downdraft biomass gasifiers is usually around 10 kW_e. In the following section, we present a theoretical case where any capacity of biomass gasifier is feasible and the initial gasifier capital costs are as for Gasifier A (see Table 3). The resulting effect on LCOE is shown in Fig 8. The proportion of power generation from biomass gasification was varied from 0 to 100%, shown on the horizontal axis. The LCOE was plotted on the primary vertical axis (left), while the secondary vertical axis (right) shows the capacity of each of the components (PV, biomass, batteries) with different units. The scale of y-axes are not consistent across Fig. 8a and 8b.

(a) PV–Bio (0.5%)



(b) PV–Bio (4%)



(c) PV–Bio

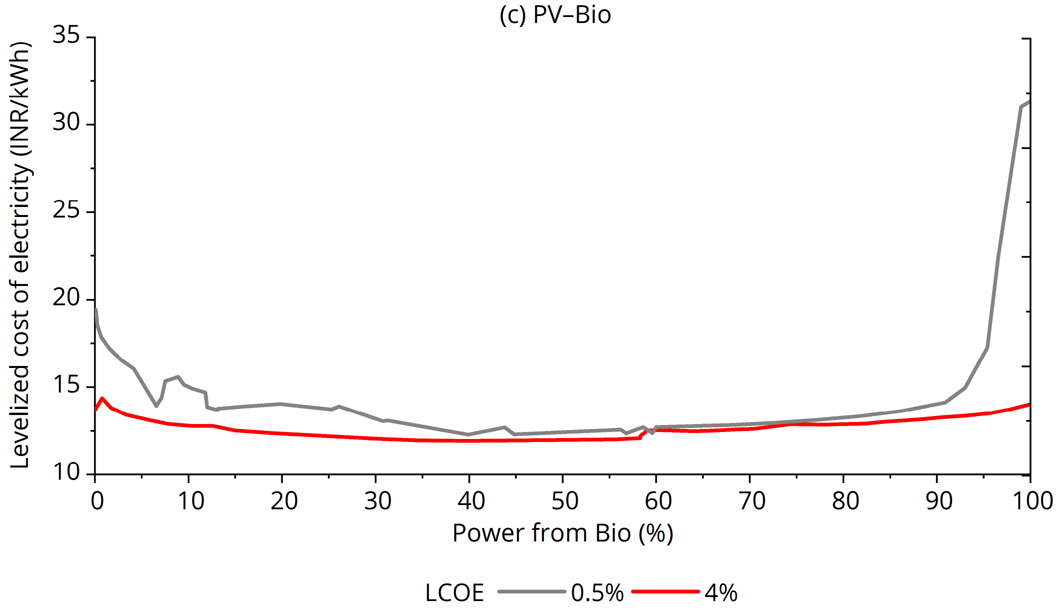


FIG. 8: TRADE-OFFS INVOLVED IN DESIGNING HYBRID PV–BIO OFF-GRID MINI-GRIDS AT (A) 0.5% AND (B) 4% ANNUAL CAPACITY SHORTAGE, AND (C) COMPARISON OF LEVELIZED ELECTRICITY COST FOR 0.5% AND 4% CAPACITY SHORTAGE.

In a system with 0.5% annual capacity shortage (Fig. 8a), the LCOE follows the same qualitative behavior as the storage capacity in the hybrid system. 100% solar or 100% biomass gasification cases require the largest battery banks to overcome intermittency of solar and to cover for gasifier maintenance times, respectively. This leads to a sharp increase in system LCOE for single-source generation systems. However, if solar and biomass are used in combination, the dependency on battery bank can be minimized. The optimal system configuration had a biomass power component of 45%, and a minimum LCOE of 12 INR/kWh.

If the capacity shortage constraint is relaxed to 4%, the LCOE is considerably lower and less sensitive to the size of battery bank (Fig. 8b). In this case, the LCOE is more dependent on the total generation capacity of the system. The optimal energy mix was found to be around 43% of power generation capacity from biomass gasification with LCOE around 12.5 INR/kWh (Fig. 8c), similar to the 0.5% annual capacity shortage case. We attribute this to the fact that less reliable power supply can accommodate more solar power generation which is cheaper, so the LCOE is unaffected by higher reliability requirement, as seen in Fig. 2.

To summarize, when designing hybrid mini-grids, there is an interplay between the mix of technologies, the reliability requirement, and their impact on LCOE. Mini-grid designers should carefully consider the annual capacity shortage that is acceptable to consumers. If a high level of reliability is desired, the costs can be reduced by minimizing the storage capacity; otherwise, the generation capacity should be lowered to save costs.

4. Conclusions

Solar PV, biomass gasification and diesel generation were compared for use in mini-grids for rural electrification using Uttar Pradesh, India, as a case study representative of other nations in the Global South. Standalone systems and hybrid configurations (PV–Bio and PV–Diesel) were simulated and optimized based on the levelized cost of electricity using HOMER. The key findings of this study are summarized below:

- For 4 % annual capacity shortage, solar PV was found to have lowest LCOE of 13.7 INR/kWh (0.20 USD/kWh) amongst standalone options
- Biomass gasification is not as commercially attractive as solar PV in a standalone context, even though it offers significant cost advantages if high reliability (1–4% shortage) is desired.
- Hybrid solar PV and biomass gasification systems potentially offer the maximum resilience to operational disruptions, and most reliable supply of power at lowest LCOE (below 12 INR/kWh i.e. 0.17 $/kWh)
- Grid-connected mini-grids resulted in LCOE reductions of up to 30–50%, and the findings held across weak, moderate and strong grid power supply.

We conclude that hybrid solar and biomass gasification-based mini-grids theoretically have potential to provide electricity at a cheaper cost than their standalone parts. This study also highlighted the theoretical trade-offs between service reliability and project economics. However, the current and future consumer demand and degree of service reliability required must be carefully considered during system design. Finally, the operational feasibility needs to be validated by field testing of hybrid mini-grids, which are more complex and require more rigorous training of staff, a notable challenge in rural markets facing shortages of skilled labor.

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Declaration of interest

The authors do not have any competing interests to declare.

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Highlights

- Hybrid PV–biomass or PV–diesel systems offer higher reliability at lower cost
- PV is cheaper than biomass gasification mini-grids for productive energy provision
- Grid-connected PV offers lowest LCOE over 20 years for strong and weak grid supply
- LCOE of biomass systems is highly sensitive to biomass requirement and maintenance
- PV–biomass systems appear resilient to operating parameters but lack field testing

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: