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Multiyear Load Growth Based Techno-Financial Evaluation of a Microgrid for an Academic Institution

ABHISHEK KUMAR[1], (Graduate Student Member, IEEE), ARVIND R. SINGH[2], YAN DENG[1], XIANGNING HE[1], (Fellow, IEEE), PRAVEEN KUMAR[3], (Senior Member, IEEE), AND RAMESH C. BANSAL[2], (Senior Member IEEE)

[1]College of Electrical Engineering, Zhejiang University, Hangzhou 310027, China
[2]Department of Electrical, Electronics and Computer Engineering, University of Pretoria, Pretoria 0002, South Africa
[3]Department of Electronics and Electrical Engineering, IIT Guwahati, Guwahati 781039, India

Corresponding author: Abhishek Kumar (abhi@zju.edu.cn)

ABSTRACT An escalating energy demand can be seen especially in developing and fast-growing economies such as India. Conventional energy resources meet most of the energy demand. The alarming issue of global warming and the dependency on fossil fuels to meet the energy demand has motivated the use of clean energy sources. In this context, the educational institutions with high electricity consumption in India have been planning to opt for locally available renewable energy sources to meet their electricity demand. Even one of the most crucial issues in such academic institutions is the food waste management. Most of the institutes, give up their food wastage to piggeries which are directly fed to animals or discarded or dumped irrationally. In this paper, an optimal microgrid solution using locally available energy resources for a real physical location considering its real time-power demand is proposed. Various scenarios and different combinations of energy sources, such as solar photovoltaic, food waste based biogas plant, and a diesel generator as backup have been considered along with batteries as storage in off-grid and grid-connected systems. Hybrid optimization of multiple electric renewables (HOMER) PRO software package is utilized for detailed technical and financial analysis with a multiyear growth approach to determine the optimal energy system, which is unlikely observed in literature so far. The detailed analysis results illustrate that photovoltaic contributes most of the electricity being generated in all the scenarios. The renewable fraction is comparatively high in the off-grid system in the range of 92% to 100% as compared with 63% to 80% in grid-connected systems. The results obtained also show that levelized cost of electricity is low in case of grid-connected systems varying between 0.18 Indian National Rupee (INR)/kWh to 1.39 INR/kWh in contrast to 11.96 INR/kWh to 18.47 INR/kWh for off-grid systems.

INDEX TERMS Microgrid, hybrid energy system (*HES*), renewable energy, HOMER PRO, biogas, food waste management.

I. INTRODUCTION

With threats of frequent climatic changes, the global community at the 21st Conference of the Parties (*COP 21*) of the United Nations Framework Convention on Climate Change (*UNFCCC*) held in Paris reached a milestone to not only to combat the frequent climatic changes but also to strengthen the steps towards a sustainable development with low carbon footprint [1]. The agreement's centrally aimed to take rigorous efforts globally in order to keep the global temperature rise well below 2°C this century and to make necessary efforts to limit the temperature rise not more than 1.5°C [1], [2]. Environmental friendly power generation is the only solution to reduce the greenhouse gas emission which helps in creating an additional carbon sink. In developing nations, an increase in energy demand can be easily observed. Renewable energy has proved to be a sustainable alternative in overcoming the energy crisis as well as in reducing the greenhouse gas emission without hindering the economic growth. With a 7.6 % GDP growth rate in 2015 and a projected GDP growth rate of 7.9 % by 2018, India has become one of the fastest growing major economy in the world [3]. Due to its rapid economic growth, several policies are introduced to press ahead for its modernizations and expansions in manufacturing doubling its energy consumption since 2000. Even though having 18 % of world population, India uses only 6% of the world's primary energy [4]. For achieving its development goals to upkeep its growing economy, production of surplus energy is vital. The economic growth is escalating the electricity demand in all sectors (industry, transport, residential, services, and agriculture). The electricity demand of India is projected to rise by an average of 4.9 % per year in all sectors and is most likely to be accounted for 17 % of the increment in global electricity consumption by 2040 [4]. The total installed capacity as on 31.03.2017 of India is 330261 MW, most of which is contributed by thermal power (coal, gas, and oil) having a share of 67.1% [5]. The renewable energy sources only share 17.34% of total electrical production. Figure 1 illustrates the share of electricity production from various sources in India in 2017.

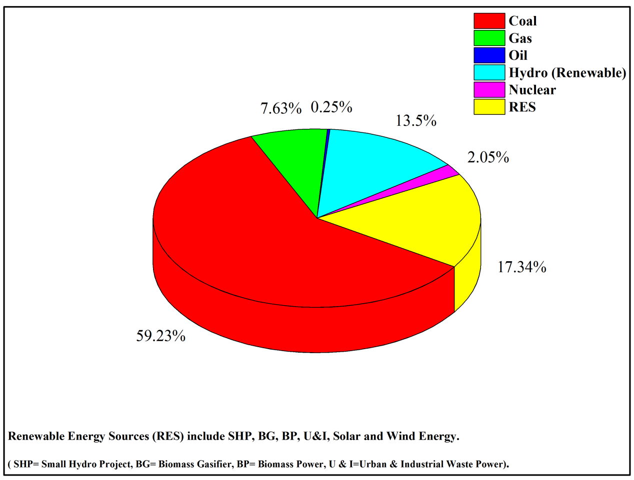


FIGURE 1. Electricity generation from various sources in India (2017).

India has planned to follow a cleaner path towards its energy needs required for its development and has established goals to use renewable energy by expanding the portion of renewable capacity by more than 5 times from 32 GW in 2014 to 175 GW in 2022 [6], [7]. Even several targets have been set in the Intended Nationally Determined Contributions (*INDC*) by 2030 such as, reducing the emission of GDP by 33-35 % from the 2005 level along with the creation of additional carbon sink of 2.5-3 billion tonnes and commitment for 40 % cumulative electricity power from renewable energy sources [6]. However, without a proper energy planning and participation from all the consumers' side (industries, domestic, government institutions, educational institutions, etc.), it is not possible to fulfill the energy needs. A proper understanding of the supply and demand is very crucial for energy planning which is full of uncertainties at every level and can only be understood with the application of decision analysis reported by Prasad *et al.* [8], [9] and Bansal [10]. A detailed application and methodologies based on multi-criteria decision analysis for energy planning with a perspective of sustainable development have been outlined in [7] and [11]. Even integrating distributed generations in the current power system has many challenges which are detailed in [12]–[14].

The educational institutes in India are more of an urban ecosystem having higher electricity consumption. India's higher education system is third in the world. It has 42 central universities, 581 state university (public 353 and private 228), 127 deemed university, 71 institutes of national importance and 5 institutions functioning under the State Act respectively [11]. Also, the number of colleges increased to 38056 reported in 2016 [15]. Higher educational institutes in India are planning to reduce their electricity consumption from the grid supply by using microgrids based on locally available renewable energy sources. In such campuses, food waste management is also a prevalent issue which needs to be addressed for better health perspectives [16]. Approximately on an average daily 1.5 tonnes of food and other kitchen waste is produced from such institutes. No proper waste management system is in place, and most of the food waste is given to pig farms to be fed to animals and sometimes discarded irrationally [16]–[19]. A solution to this problem could be energy generation based on biogas production from institute's food waste [20], [21]. By utilizing anaerobic digestion process, the food waste can be converted to biogas and could be utilized for several purposes such as heating, cooking, etc. [16]–[25]. A detailed review of biomass gasification process from solid waste for Indian perspective is reported in [17], [21], and [25]. Many studies exist in the literature about microgrid design based on renewable energy sources utilizing different methods (soft computing techniques), optimization techniques (single and multiple) and popular software tools [26]–[36]. A critical review of recent literature based on HOMER for techno-financial analysis of hybrid energy systems is illustrated in following sub-section.

A. FEW RECENT STUDIES BASED ON HOMER FOR FEASIBILITY STUDY OF HES

Table 1 illustrates some recently published studies using HOMER software of HES for different locations based on solar photovoltaic (*SPV*), wind energy (*WT*), micro-hydro or hydrokinetics (*HY*), biomass generators (*BM*), biogas generator (*BG*), fuel generators based on natural gas or diesel (*DG*) along with different energy storage systems such as batteries (*BA*), flywheel (*FW*), hydrogen-based fuel cell (*FC*) and pump hydro storage (*PHS*) respectively in isolated or grid connected schemes. The size of bidirectional converters (*BC*) wherever applicable is also outlined. The studies are summarized based on their location, year, architecture (isolated centralized scheme (*ICS*), isolated decentralized scheme (*IDS*), grid centralized scheme (*GCS*) and grid decentralized schemes (*GDS*)) along with technical aspects (component details, dispatch strategy (*DS*) such as load

TABLE 1. Recent feasibility studies on HES using HOMER [37]–[94].

Sl. No.	Location	Year	Architecture	TECHNICAL ASPECTS														
				COMPONENTS												DS	LOAD TYPE	RF (%)
				SPV	WT	HY	BG	BM	DG	GD	BC	FC	BA	PHS	FW			
1.	Tsumkwe, Namibia [37]	2017	ICS	✓	×	×	×	×	✓	×	✓	×	✓	×	×	NM	Remote village (community)	46
2.	Kilis, Southern Turkey [38]	2017	ICS	✓	×	×	×	×	✓	×	✓	×	✓	×	×	CC	Residential (summer house)	79
3.	Iran [39]	2017	ICS	✓	✓	×	×	×	×	×	✓	×	✓	×	×	NM	Residential (Forestry Camp)	NM
4.	Andean region [40]	2017	ICS,ISD	✓	✓	✓	×	×	×	×	✓	×	✓	×	×	NM	Community	100
5.	Hendijan County, Iran [41]	2017	GCS	✓	✓	×	×	×	✓	✓	✓	×	✓	×	×	NM	Hydrogen based load	NM
6.	Sarawak, East Malaysia [42]	2017	ICS	✓	×	×	×	×	×	×	✓	✓	✓	×	×	LF	Village (50 households)	100
7.	South Korea [43]	2017	ICS	✓	✓	×	×	×	✓	×	✓	×	✓	×	×	NM	City load	100
8.	Shafar, Yamen [44]	2017	ICS	✓	✓	×	×	×	✓	×	✓	×	×	×	×	LF	Household	90
9.	Varanasi, India [45]	2017	ISD	✓	×	×	×	×	×	×	×	×	×	×	×	NM	Small home light system	NM
10.	Sabah, Malaysia [46]	2017	ICS	✓	×	×	×	×	✓	×	✓	×	✓	×	×	LF CC	Community	100 100
11.	Jhawani, Tezpur, India [47]	2017	ICS, GCS	✓	×	×	×	✓	✓	✓	✓	×	✓	×	×	NM	Remote village	93 91
12.	India [48]	2017	ICS	✓	×	×	×	×	×	×	✓	✓	✓	×	×	CC LF	Academic building	100
13.	Chile [49]	2017	GCS	×	✓	×	×	×	×	✓	✓	×	×	×	×	NM	Community	NM
14.	South China Sea [50]	2017	ICS	✓	✓	×	×	×	✓	×	✓	✓	✓	×	✓	CC	Community (Island)	91 90
15.	Colombia [51]	2017	ICS	✓	✓	×	×	×	✓	×	✓	×	✓	×	×	NM	Remote Village	NM
16.	Saudi Arabia [52]	2017	ICS	✓	✓	×	×	×	×	×	✓	✓	✓	×	✓	NM	Community	100
17.	USA [53]	2016	GDS	✓	×	×	×	×	×	✓	✓	×	✓	×	×	NM	Residential	NM
18.	Oujda, Morocco [54]	2016	ICS	✓	✓	×	×	×	×	×	✓	×	✓	×	×	CC	Residential	100
19.	South Korea [55]	2016	ICS, GCS	✓	✓	×	×	×	✓	✓	✓	×	✓	×	×	NM	Academic	100 100
20.	Chamoli, India [56]	2016	ICS	✓	✓	✓	✓	✓	×	×	✓	×	✓	×	×	CC	Remote village	100
21.	Almora, India [57]	2016	ICS	✓	×	✓	✓	✓	✓	×	✓	×	✓	×	×	CC	Remote village	94
22.	Aden, China [58]	2016	ICS	✓	×	×	×	×	✓		✓	×	✓	×	×	NM	Oil tanker ship Land (site specific)	5.7 89.7
23.	Kadayam, India [59]	2016	ICS	✓	✓	✓	×	×	×	×	✓	×	✓	×	×	CC	Remote village	100
24.	Brochet, Canada [60]	2016	ICS	×	✓	×	×	×	✓	×	✓	×	✓	×	×	NM	Community	47
25.	Bangladesh [61]	2016	ICS	✓	×	✓	×	×	✓	×	✓	×	✓	×	×	NM	Remote village	64.4
26.	Kutubdia Island, Bangladesh [62]	2016	ICS	✓	✓	×	×	×	✓	×	✓	×	✓	×	×	NM	Community	87.9
27.	Colombia [63]	2016	ICS	✓	✓	×	×	×	✓	×	✓	×	✓	×	×	NM	Remote Village	99
28.	Southern Iran [64]	2016	ICS, GCS	✓	✓	×	×	×	✓	✓	✓	×	✓	×	×	NM	Community	0-43.9
29.	Khuzestan, Iran [65]	2016	ICS	✓	×	×	×	×	×	×	✓	×	✓	×	×	NM	Community	100
30.	Malaysia [66]	2016	ICS, GCS	✓	×	×	×	×	×	✓	✓	✓	✓	×	×	LF	Hospital	82
31.	Malaysia [67]	2016	GCS	✓	×	×	×	×	×	✓	✓	×	✓	×	×	NM	Community	33
32.	Patiala, India [68]	2016	ICS, GCS	✓	✓	×	×	✓	×	✓	✓	×	✓	×	×	LF	Community	100
33.	Egypt [69]	2016	ICS	✓	✓	×	×	×	×	×	✓	✓	✓	×	×	NM	Agricultural Load	100
34.	Vesleskarvet, Antarctica [70]	2016	ICS	×	✓	×	×	×	×	×	✓	×	✓	×	×	NM	Community Load	100
35.	Saudi Arabia [71]	2016	ICS	✓	✓	×	×	×	×	×	✓	×	✓	×	×	NM	Community	100
36.	Almora, India [72]	2015	ICS	✓	✓	✓	✓	✓	✓	×	✓	×	✓	×	×	CC	Remote village	92.7
37.	Garisaa, Kenya [73]	2015	ICS	✓	✓	×	✓	×	✓	×	✓	×	✓	×	×	NM	Remote village	100
38.	Turkey [74]	2015	ICS, GCS	✓	✓	×	×	×	×	✓	✓	✓	✓	×	×	NM	Island	100

TABLE 1. ***(Continued.)*** **Recent feasibility studies on HES using HOMER [37]–[94].**

39.	Chennai, India [75]	2015	*ICS, GCS*	✓	✓	×	×	×	✓	✓	✓	✓	✓	×	×	*NM*	Telecom Load	NM
40.	Makkah, Saudi Arabia [76]	2015	*GCS*	✓	×	×	×	×	×	✓	✓	×	×	×	×	*NM*	Community	33
41.	Bouzareah, Algerian [77]	2015	*GCS*	✓	✓	×	×	×	×	✓	✓	×	×	×	×	*LF*	Community	24
42.	Bangladesh [78]	2015	*ICS*	✓	✓	×	×	×	×	×	✓	×	✓	×	×	*NM*	Remote village	43
43.	Nigeria [79]	2015	*ICS*	✓	✓	×	×	×	×	×	✓	×	✓	×	×	*LF*	Remote village	71
44.	United Kingdom [80]	2015	*IDS, GDS*	✓	✓	×	×	×	×	×	✓	×	×	×	×	*NM*	Residential Load	NM NM
45.	Margarita Island,Venezuela [81]	2015	*IDS*	✓	✓	×	×	×	✓	×	✓	×	✓	×	×	*NM*	Residential Load	
46.	Democratic Republic of Congo [82]	2015	*ICS*	✓	×	×	×	✓	×	×	✓	×	✓	×	×	*NM*	Academic Building	100
47.	Corvo Island, Azores [83]	2015	*ICS*	×	×	×	×	✓	×	×	×	×	×	×	×	*CC, LF*	Island	NM
48.	Spain [84]	2014	*GCS*	✓	✓	✓	×	✓	✓	✓	×	×	×	×	×	*CC*	Sports Building	NM
49.	Hong Kong[85]	2014	*ICS*	✓	✓	×	×	×	×	×	✓	×	✓	×	×	*CC*	Remote Island	100
50.	Hong Kong [86]	2014	*ICS*	✓	✓	×	×	×	×	×	✓	×	×	✓	×	*NM*	Remote island	100
51.	Jeju, South Korea [87]	2014	*ICS, GCS*	✓	✓	×	×	×	×	✓	✓	×	✓	×	×	*NM*	Remote island	100
52.	Netherlands [88]	2014	*GCS, ICS*	✓	✓	×	×	×	✓	✓	✓	×	✓	×	×	*NM*	Community water treatment plant	79
53.	Iran [89]	2013	*ICS*	✓	×	×	×	×	✓	×	✓	×	✓	×	×	*NM*	Rural household	35
54.	Saudi Arabia [90]	2013	*ICS*	×	✓	×	×	×	×	×	×	×	×	×	×	*NM*	Community	100
55.	Ajloun city, Jordan [91]	2013	*GCS, ICS*	✓	✓	×	×	×	✓	✓	✓	×	✓	×	×	*NM*	Residential	62
56.	Kerala, India [92]	2012	*ICS*	✓	×	✓	×	✓	×	×	✓	×	✓	×	×	*NM*	Remote village	100
57.	Lesvos, Greece [93]	2011	*ICS*	×	✓	×	×	×	✓	×	×	×	×	×	×	*NM*	Community	NM
58.	Ethiopia [94]	2010	*ICS*	✓	✓	×	×	×	✓	×	✓	×	✓	×	×	*CC, LF*	Community	51

following (*LF*) or cycle charging (*CC*), load type and renewable fraction (*RF*)) respectively. *NM* in Table 1 specifies the quantities which are not mentioned in the studies.

Most of the studies as illustrated in Table 1 are carried out in *ICS* schemes for remote locations considering a few energy combination scenarios mostly based on *SPV, WT, DG* and *BA*. Only a handful of studies have considered studying grid extension scenarios in comparison with isolated scenarios [95]. A very few studies focusing on design of microgrid based on *BG* or *BM* in combination with other renewable energy technologies is reported. Kumar *et al.* [96] have presented an optimal design study of a grid-connected energy system (*SPV* + food waste biogas) for academic institute in India. A hybrid power system consisting of bio-generators (*BG* and *BM*) with *SPV, HY, DG* and *BA* for a remote village in India has been reported in [57], [72], and [97]. A detailed techno-financial analysis of a hybrid energy system for a remote village located in Kerala, India in off-grid configuration consisting of *SPV, HY,* biomass-based generator along with *BA* as storage has been discussed in [92]. Kumar *et al.* [98] using three different scenarios based on available local energy resources have evaluated a hybrid microgrid for a remote community in North-eastern state of India. A detailed techno-financial analysis using single objective optimization for the same region is reported in [99]. Using HOMER, analysis and design of a microgrid considering 7 scenarios with a combination of energy resources (*BG* with *SPV*) and storage technologies (*BA, FC*) for a rural area in West Bengal with an overall electric load of 22MWh/year is reported in [100]. Economic evaluation using HOMER for a biomass-based energy system for a better integration with other renewable energy sources has been studied by Montuori *et al.* [84]. This study primarily focus on the following research gaps:

i) In none of the studies outlined so far from the existing literature accounts for the yearly load growth, which seems highly unrealistic towards the design of energy system [30]–[99], [101], [102]. All the studies have evaluated the *HES* on the basis of existing load data over the project lifetime. The project lifetime is taken around 20 to 25 years for calculation of various cost incurred mainly the cost of energy which relies mostly on the lifetime of renewable energy technologies (*RETs*). In real application, even technologies with higher lifespan such as *SPV* are unable to produce the same amount of electricity every year due to reduction in its efficiency over a period of time. So, without considering a yearly load growth while designing the energy system can give not only technical errors but also financial mistakes.

ii) Also, in many works the dispatch strategy or energy management system (*EMS*) for evaluating the *HES* is not mentioned which itself is a big anomaly is such studies [37], [38], [40], [43], [45], [47], [49], [87]–[93], [95], [96]. Without having a proper dispatch or *EMS*, the results obtained and illustrated seems very hypothetical. Most of the systems being evaluated in literature also lack clear mention of the cost incurred in civil works for installation of *SPV, WT* or other technologies and only the capital cost of the technologies for feasibility studies have been considered.

iii) In [95], system fixed capital cost (includes civil, logistics, wages, etc.) and operation and maintenance cost (*O&M*) for the project lifetime is considered on the whole for all the *RETs*. Even no consideration is taken up for the land cost which accounts for almost 5-7 % of the total capital cost depending upon the type of *RETs* [101]. According to Central Electricity Regulatory Commission (*CERC*), Government of India during energy project execution, the capital cost (*CPC*) of the technologies shall be inclusive of all "*capital works like plant and machinery, civil works, erection and commissioning, financing and interest during construction, and evacuation infrastructure up to inter-connection point*" [101].

iv) In [47], [56], [57], [68], [72], [73], [82], [92], [97], [102], and [103], there is no clear mention of the *CPC* and *O&M* cost of biomass digester. Due to this error may occur in the calculation of levelized cost of electricity (*LCOE*), as it is dependent on capital as well as *O&M* cost. Even if the capital cost of the anaerobic digester is included in the capital cost of the generator it is not wise to do so, as the *O&M* cost of the biogas generator is dependent on an hourly basis and anaerobic digester *O & M* cost on yearly basis. However, it is possible to include the digester *O&M* cost in terms of price/kg of biomass feedstock consumed, then the digester *O&M* could be included in the biomass feedstock cost [104].

In this work, a microgrid is designed using the locally available energy sources for a real physical location (Indian Institute of Technology, Guwahati) considering the real power demand. A detailed multiyear-based techno-financial analysis of energy system is done using HOMER PRO (hybrid optimization of multiple energy resources) software, which is highly unlikely to be observed in literature so far. For this study, various benchmark costs as prescribed by the *CERC*, Government of India is considered [101]. This paper evaluates energy system based on different combinations of energy sources (solar photovoltaic, food waste based biogas plant and diesel generator as backup) along with batteries as storage in off-grid and grid-connected systems considering a yearly load growth.

A total of 12 microgrid scenarios were considered based on the combination of energy resources and storage in off-grid and grid connected mode for the analysis with yearly electrical load growth. Also, two different dispatch strategies namely, *CC* and *LF* are employed for energy management and evaluation in all the scenarios. A detailed comparative analysis of the technical and economic results obtained based on *CC* and *LF* is also illustrated. The paper is outlined as follows: section 2 provides insights of the new multiyear module of HOMER PRO utilized to perform this study and section 3 provides the detailed description of the real physical location which has been taken as the case study for the analysis. Section 4 comprises of various technical and financial parameters along with various system configuration and scenarios taken for analysis. Section 5 shows the analysis results and section 6 finally concludes the paper.

II. DESCRIPTION OF MULTIYEAR MODULE OF HOMER PRO

Around the mid of 2016, HOMER Energy released a new version of HOMER Pro with a new Multi-Year module which allows one to model specific critical parametric changes such as grid price escalations, electrical load growth, *SPV* degradation, etc., which may occur during the project lifetime. Figure 2 shows the new multiyear module added to HOMER PRO [104], [105].

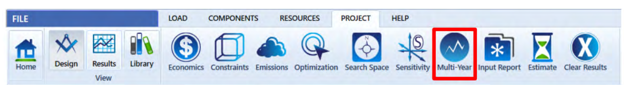


FIGURE 2. Multiyear module of HOMER PRO [105].

The Multi-Year inputs allow users to specify the percentage growth or degradations each year as illustrated in Figure 3.

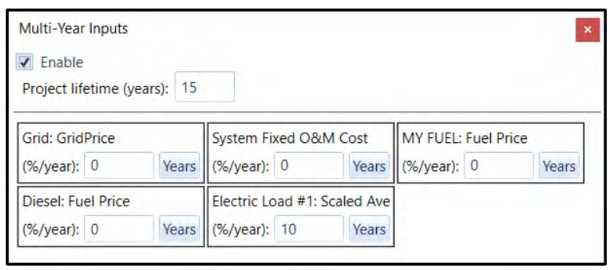


FIGURE 3. Multiyear Input window of HOMER PRO [105].

The designer is free to choose and can consider the variations occurring in the *O&M* costs, *SPV* degradation, diesel fuel prices, and primary electrical load changes. In case, if changes in some parameters are not required, it can be done by setting the values to zero. Also, if the user needs to model changes in a specified parameter, it can be achieved by including constant percentage value by which that component could change every year [105]. The new module adds several new features to HOMER's results. Simulation results and various parametric variations can be looked on a yearly basis over the project life. As illustrated in Figure 4, the module

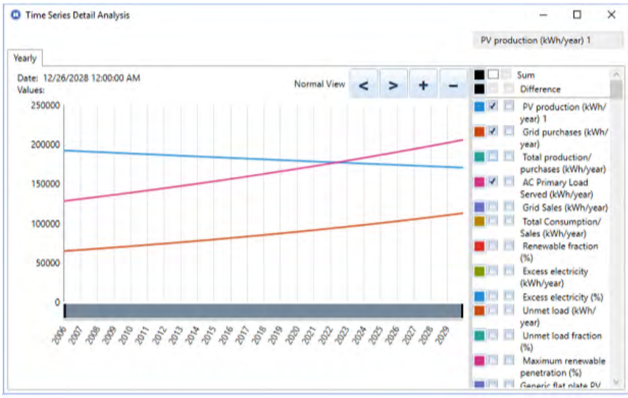


FIGURE 4. Multiyear plot window of HOMER PRO [105].

also consists of the Multi-Year plot, which can be utilized to plot any resulting quantity on project lifetime.

III. DESCRIPTION OF THE INDIAN INSTITUTE OF TECHNOLOGY (IIT), GUWAHATI CAMPUS

A. LOCATION AND POPULACE

IIT Guwahati (*IIT GHY*) campus is located on the north bank of majestic river the Brahmaputra, neighboring to the North Guwahati town of Amingaon at 26.1929° N, 91.6951° E. With spreading over 285 hectares plot of land, the campus includes a total of eleven departments and three inter-disciplinary academic centers covering all the major engineering, science, and humanities disciplines. The campus populace comprises of about 5186 students (2570 undergraduate and 1913 postgraduate) on rolls, 372 faculty members and 386 support staff [106].

B. ELECTRICAL LOAD DEMAND INFORMATION OF CAMPUS

The electricity grid supplies IIT's current energy demand. The scaled energy demand is approximately around 60379 kWh/day with a peak load of 3075 kW and an average demand of 2515.8 kW. Figure 5 illustrates a typical load profile of campus with hourly variation.

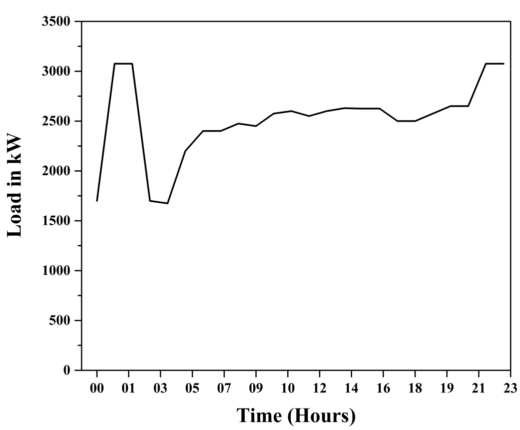


FIGURE 5. A typical hourly profile of electrical load of IIT, GHY campus.

The load factor was calculated to be 0.82. The average power factor obtained from the *IIT GHY* substation is measured to be 0.97.

C. CAMPUS METEOROLOGICAL DATA

The required meteorological data of the campus were obtained using renewable energy resource website sponsored by NASA [107]. The average annual solar isolation was around 4.75 kWh/m2/day with an average solar clearness index of 0.548. Figure 6 illustrates the average monthly profile of solar isolation along with clearness index. However, the wind potential at *IIT GHY* location is not tangible as surrounded by mountains due to which wind-based generating systems has not been considered in this study.

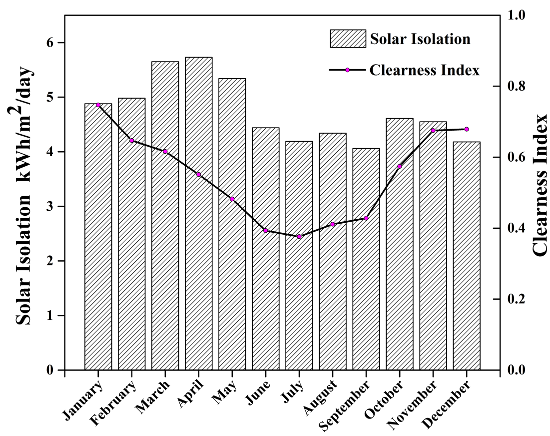


FIGURE 6. Average monthly profile of solar isolation and clearance index at IIT GHY [107].

D. CAMPUS AVAILABLE BIOMASS

In *IIT GHY* campus on an average 4 tonnes/day, kitchen waste is thrown out. Most of the waste is mainly taken by the local piggeries and is fed to the animals, which are more likely to be thrown away unreasonably by the farm owners. This wastage can be used for the production of electricity using anaerobic process and in turn, can efficiently provide a better solution for the waste management of the Institute. Figure 7 illustrates the monthly available average biomass in *IIT GHY* campus.

IV. VARIOUS TECHNICAL AND FINANCIAL PARAMETERS USED FOR ANALYSIS

A. LOAD GROWTH ASSUMPTIONS

A detailed review based on the application of soft computing techniques for electrical load forecasting has been reported in [108]. An overview based on long-term load forecasting with the use of specific models such as qualitative, quarantine, time-series, stochastic, etc. has been introduced in detail for developing utilities by Kandil *et al.* [109]. The use of econometric models such as ARDL and PAM for forecasting electrical consumption of Ghana till 2020 has been done in [110]. However, at disintegrated levels such as educational institutes, the use of such models and methods are not suitable and too complicated. But, a simple

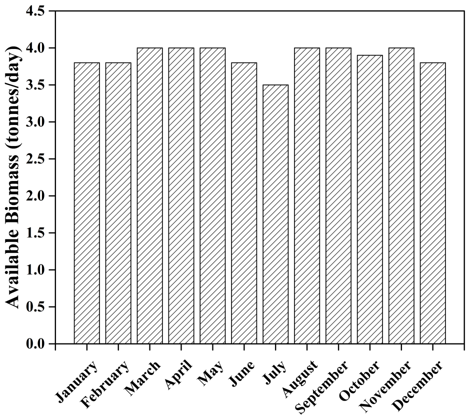


FIGURE 7. Monthly profile of average available biomass in IIT GHY Campus.

approach based on the current strength of faculty, student, staff, etc. and their annual strength growth can lead the way for approximate projection of load growth. According to, to *IIT GHY* annual report of 2014-2105 [106], every year a 6.03% and 8.77 % growth in students and faculty strength is observed respectively. Recently, the Kakodkar Committee report [111] has suggested that over the next decade, IIT's (19 existing and 4 new)should increase their strength to 16000 faculty members and 160000 total student strength, with 40000 at the Ph.D. level, 40000 at the Masters level and 80000 UG students. The committee also emphasizes on producing 10000 Ph.D. scholars every year. So, taking all the above numbers into account, to achieve the above-said targets, all the IIT's must increase their strength by approximately 8-10 % every year. Based on these factors, a 10 % annual electric load growth is considered in this research work.

B. DETAILS OF VARIOUS MICROGRID ELEMENTS WITH THEIR COST

Depending upon the available resources depicted in above sections and the load demand, following components are considered for designing of the microgrid: solar pv, diesel generator, grid, batteries, converters, biogas generator along with anaerobic biogas digester plant. The details of each component with their mathematical modelling and various economic parameters utilized in this study have been explained below:

1) ANAEROBIC BIOGAS DIGESTER PLANT

As the conventional biogas plant can handle only cow/buffalo dungs (gobar) or human waste, we have taken BARC's NISARGRUNA biogas plant for conversion of biogas from available biomass stock at *IIT GHY* for this analysis. It can efficiently process any biodegradable waste including kitchen waste, paper, grass, gobar, dry leaves, etc. Even this plant offers a "Zero garbage, Zero effluent method" for solid waste management [112]. The *CPC* and *O & M* cost of 1 tonne/day capacity plant is taken as INR 1600000 and 100000 respectively [96], [112]. As the production of Biomass from *IIT GHY* is approximately 4 tonnes/day, a digester plant of that capacity is required for the production of biogas. Dhamodharan *et al.* [24], have presented a study to evaluate the production of methane gas obtained from the food wastage at *IIT GHY* campus with a detailed study on the effects of livestock dungs on the anaerobic digestion of the food waste. Approximately, the NISARGRUNA biogas plant can produce biogas having 70 -75 % of methane content from the kitchen waste [24], [25], [112].

2) BIOGAS GENERATOR (*BG*)

A 1 kW *BG* is assumed to have *CPC* of INR 50000/kW [72], [97] and the fuel for *BG* is from *IIT GHY* SO, THE *O & M* cost/hr is zero. a search space in the range of (100-1000) kW is considered for the analysis. the generated power output (P_{BG}) and annual energy production (E_{BG}) can be obtained using the following equation [28], [72], [105]:

$$P_{BG} = \frac{[GY_{AD} \times C_{V(biogas)} \times \eta_{BG}]}{860 \times (t_h/day)} \quad (1)$$

$$E_{BG} = P_{BG} \times 8760 \times CF \quad (2)$$

where GY_{AD} is the total biogas generated or produced from digester in m^3/day, $C_{V(biogas)}$ is the calorific value of the biogas produced which is around 4700 kcal/m^3 [28], η_{BG} is the electrical conversion efficiency of *BG* (around 27 % [28]), t_h is the hours of operation of *BG* and *CF* is the utilization factor in percent value.

3) SOLAR PHOTOVOLTAIC (*SPV*)

A fixed type *SPV* panel is considered with a *CPC* of INR 50502/kW as per the benchmark capital cost by CERC [101]. the *O & M* cost is taken as INR 700/kW per year. The capital cost as mentioned in introduction section already includes module cost, civil and general works, mounting structures, power conditioning unit (inverter), evacuation cost, preliminary and pre-operative expenses as recommended by *CERC* [101]. the power output (p_{spv}) of *SPV* array system as calculated by HOMER is given by following equation [105]:

$$P_{SPV} = RC_{SPV} DF_{SPV} \left[\frac{G_{SR}}{G_{SR@STC}}\right] \times \left[1 + \alpha_p (T_{SPV} - T_{SPV@STC})\right] \quad (3)$$

where, RC_{SPV} is the rated panel capacity of the *SPV* in kW, DF_{SPV} is the *SPV* derating factor in percent values (%), G_{SR} is the incident solar radiation on the *SPV* array in kW/M^2, $G_{SR@STC}$ is the radiation at standard testing condition (*STC*) in kW/M^2, α_p is the *SPV* temperature coefficient of power in %/°C, T_{SPV} is the rated *SPV* cell temperature in °C and $T_{SPV@STC}$ is the cell temperature at *STC* IN °C respectively.

4) DIESEL GENERATOR (*DG*)

As shown in Table 2, *IIT GHY* has a total of 8 *DG* with an overall rating of 9000 kVA. Since the *DGS* already are

TABLE 2. Details of components and various costs.

Sl. No.	Component Details		Capital Cost (*CPC*) (INR)	Replacement Cost (INR)	*O&M* Cost (INR)	Remarks
1.	Solar PV(Fixed Axis type)(*SPV*) [101]		50502/kW	50502/kW	700/ kW/year	Capital Cost also includes the cost of necessary power conditioning unit required to connect AC BUS or DC BUS. Land cost is not included.
2.	Anaerobic biogas digester plant [112]		1600000 for 1 tonne/day capacity plant	N/A	150000/year	The capital along with O & M cost is included in system fixed costs in HOMER for analysis. Detailed explanation in subsection 4.3.
3.	Biogas Generator (*BG*) [72, 97]		50000 /kW	45000/kW	0	As the biomass fuel is from IIT, GHY available waste, O & M cost is taken as zero.
4.	Diesel Generator (*DG*)	(i) 1500 kVA	0	0	375 / hr	As all the DGs are already installed in IIT GHY campus, the capital cost is zero. The installed DGs rarely run, and moreover, it doesn't need any replacement during the project life time, so the replacement cost is assumed zero. The O & M cost shows the approximate values only, as per the data obtained from IIT GHY Campus sub-station.
		(ii) 1500 kVA	0	0	375 / hr	
		(iii) 750 kVA	0	0	190 / hr	
		(iv) 1250 kVA	0	0	310/ hr	
		(v) 1250 kVA	0	0	310/ hr	
		(vi) 750 kVA	0	0	190 / hr	
		(vii) 750 kVA	0	0	190 / hr	
		(viii) 1250 kVA	0	0	310/ hr	
5.	Bidirectional Converter (*BCon*) [72, 97]		10000/kW	10000/kW	0	
6.	Tubular flooded lead-acid batteries (*LAB*) [104, 105]	Parameters with their values	22000 for one battery.	22000 for one battery	700 /year	The capital, replacement and O & M cost of the battery is interpreted form the quotation obtained from the vendors.
		Nominal Voltage = 12 V				
		Nominal capacity = 3kWh				
		Maximum capacity = 244.97 Ah				
		Capacity Ratio = 0.329				
		Rate Constant (1/hr) = 0.597				
		Roundtrip Efficiency (%) = 85				
		Maximum Charge Current = 57A				
		Maximum Discharge Current = 133.9 A				
		Maximum Charge Rate (A/Ah) =1				

installed in the *IIT GHY*, the *CPC* is taken up as zero. The specific details regarding the *O & M* cost is illustrated in Table 2. the annual fuel (diesel) consumption (F_{DG}) value is obtained by HOMER using following equation [105]:

$$F_{DG} = \frac{F_{total}}{E_{total,gen}} \tag{4}$$

where, F_{total} is the annual fuel consumption of generator in liters/year and $E_{total,gen}$ is the electrical production on an annual basis by the generator in kWh/year. The *DG'S* average electrical efficiency (η_{DG}) is calculated using the equation below [105]:

$$\eta_{DG} = \frac{3.6.E_{total,gen}}{m_{DG}.LHV_{fuel,DG}} \tag{5}$$

where, $E_{total,gen}$ is the electrical production on an annual basis by the generator in kWh/year, m_{DG} is the mass flow rate of fuel in kg/hour and $LHV_{\text{fuel,DG}}$ is the lower heating value of fuel in MJ/kg (43.2 MJ/kg for diesel) respectively. The mass flow rate of the fuel (in this case diesel) is dependent on the *DG* hourly fuel consumption $F_{DG,Hourly}$ which is given by [105]:

$$F_{DG,Hourly} = \alpha_{dg} P_{DG,Rated} + \beta_{dg} P_{DG,out} \tag{6}$$

where, $P_{DG,Rated}$ is the rated capacity of *DG* in kW, $P_{DG,out}$ is the average hourly electrical power output of *DG* in kW, annual basis by the generator in kWh/year, α_{dg} is the intercept coefficient of the fuel curve in Liter/hr/kW and β_{dg} is the slope coefficient of fuel curve in Liter/hr/kW respectively. Hence using equation (6), the value of m_{DG} can be given as [105]:

$$m_{DG} = \rho_{DG}\left(\frac{F_{DG,Hourly}}{1000}\right) \tag{7}$$

where, ρ_{DG} is the density of fuel (diesel) in kg/m^3 which is around 820 kg/m^3 for diesel [105].

5) GRID

Assam state electricity board (aseb) provides electrical supply to *IIT GHY* at a commercial rate of INR 5.96/kWh. The energy charges for grid can be calculated with or without the net metering scheme which are as follows [105]:

a: GRID ENERGY CHARGES WITHOUT NET METERING (GEC_{WNM}) [105]

$$GEC_{WNM} = \sum_{k}^{rate}\sum_{l}^{12} E_{purchase,k,l} \cdot gec_{grid,k} - \sum_{k}^{rate}\sum_{l}^{12} E_{sells,k,l} \cdot gec_{sells,k} \tag{8}$$

where, $E_{purchase,k,l}$ is the total amount of energy in kwh being purchased from the grid in month l with applied rate k, $GEC_{grid,k}$ is the power price of grid for rate k in INR/kWh, $E_{sells,k,l}$ is the total amount of energy in kWh being sold to the grid in month l with applied rate k, $GEC_{sells,k}$ is the sells price for rate k in INR/kWh.

b: GRID ENERGY CHARGES WITH NET METERING (GEC_{NM}) [105]

In net metering scheme the energy charges can be calculated wither considering the monthly or annual net generation using following equations(9) and (10), as shown at the bottom of this page [105]:

$$GEC_{NM(monthly)} = \sum_{k}^{rate}\sum_{l}^{12}\left\{\begin{matrix} E_{m.net(grid),k,l}.gec_{grid,k} \ \ if \ E_{m.net(grid),k,l} \geq 0 \\ E_{m.net(grid),k,l}.gec_{sells,k} \ \ if \ E_{m.net(grid),k,l} < 0 \end{matrix}\right\} \tag{9}$$

where, $GEC_{NM(monthly)}$ is the energy charges in kwh when net generation is accounted monthly, $E_{m.net(grid),k,l}$ is the net energy purchased in kWh from grid (grid purchase minus grid sells) in month l during the applied rate of k, $GEC_{grid,k}$ is the power price of grid for rate l in INR/kWh and $GEC_{sells,k}$ is the sells price for rate l in INR/kWh, where, $GEC_{NM(annual)}$ is the energy charges in kWh when net generation is accounted monthly, $E_{m.net(grid),k,l}$ is the annual net energy purchased in kWh from grid (grid purchase minus grid sells) during the applied rate of k, $GEC_{grid,l}$ is the power price of grid for rate k in INR/kWh and $GEC_{sells,k}$ is the sells price for rate k in INR/kWh. For this study, a simple rate approach which allows setting a constant power price and sells back price [105] in a net metering scheme calculated on a monthly basis for grid-connected systems is considered. the sell back price to the grid is also assumed to be INR 5.96, due to commercial rates and unavailability of real-time schedule rates.

6) BATTERY STORAGE (*LAB*)

Tubular flooded lead-acid batteries (Discover 12VRE-3000TF-L) which can provide lowest cost/kWh and is suitable especially for off-grid applications is considered as storage [104]. A kinetic battery model of Discover 12VRE-3000TF-L is taken for the design of storage system. Various parameters along with battery costing are illustrated in Table 2. A string size of 20 is taken with an initial state of charge as 100 % and minimum state of charge as 20 %. The maximum discharge power by the battery storage is calculated using equation (11) [105],

$$P_{Disch\arg e} = \frac{-kcQ_{\max} + kQ_{initial}e^{-k\Delta t} + Q_{total}kc(1-e^{-k\Delta t})}{1-e^{-k\Delta t} + c(k\Delta t - 1 + e^{-k\Delta t})} \tag{11}$$

The maximum power which can be absorbed by the battery storage is calculated using equation (12) given below [105],

$$P_{ch\arg e} = \frac{kQ_{initial}e^{-k\Delta t} + Q_{total}kc(1-e^{-k\Delta t})}{1-e^{-k\Delta t} + c(k\Delta t - 1 + e^{-k\Delta t})} \tag{12}$$

where, Q_{max} is the total capacity of the storage bank in kWh, $Q_{initial}$ is the energy available in the storage during the beginning of the time step in kWh, Q_{total} is the total amount of energy available in the storage system at the beginning of the time step in kWh, c is the capacity ratio of battery storage, k is the rate constant of battery storage (1/Hr), and Δt is time step length in hours respectively. The battery storage autonomy (AT_{bat}) in hours is obtained using equation (13) [105],

$$AT_{bat} = \frac{N_{bat}V_{nbat}Q_{nbat}\left(1-{SOC_{\min}}/{100}\right)(24h/day)}{Load_{prim,avg}(1000Wh/kWh)} \tag{13}$$

Where, N_{bat} is the total number of batteries constituting the storage system, V_{nbat} is the nominal voltage of battery in volts, Q_{nbat} is the nominal capacity of a single battery in Ah, SOC_{min} is the minimum state of charge of battery in percent value (%) and $Load_{prim,avg}$ is the average main demand in kWh/day respectively.

7) BIDIRECTIONAL CONVERTER (*BCON*)

A bi-directional converter (*BCon)* is considered in the off-grid system designs. The *CPC* is considered to be INR 10000/kW [72], [97], [101]. Currently, available converters in the market are maintenance free for their lifetime, so the *O & M* cost is considered to be zero. The other specific details considered for analysis is illustrated in Table 2.

8) SYSTEM CONTROLLER [105]

The system controller in HOMER PRO allows users to specify how the system can be designed and operated during the simulations. Every controller has a unique algorithm or set of rules to control the operation of the various generators and the storages to meet the load demand. HOMER can simulate and optimize models with multiple controllers and gives the results for performance comparisons. In this analysis, two dispatch strategy namely *LF* and *CC* have been considered. in the *LF*, the designed system's power generating such as generators, grid, etc. First serve the main (primary) load and the thermal load at the lowest total costing for each time step, while keeping the operating reserve requirements. Secondary

$$GEC_{NM(annual)} = \sum_{k}^{rate}\sum_{l}^{12}\left\{\begin{matrix} E_{annual.net(grid),k,l}.gec_{grid,k} \ \ if \ E_{annual.net(grid),k,l} \geq 0 \\ E_{annual.net(grid),k,l}.gec_{sells,k} \ \ if \ E_{annual.net(grid),k,l} < 0 \end{matrix}\right\} \tag{10}$$

TABLE 3. Optimal size of various components in different microgrid scenarios.

Microgrid Design Scenario	Dispatch Algorithm	COMPONENTS							Overall Renewable Fraction (RF %)
		SPV (kW)	*BG* (kW)	*DG* (kVA)	*BCon* (kW)	*LAB* (Numbers)	Grid		
							Total energy Purchased (kWh)	Total energy Sold (kWh)	
1st	CC	60000	0	0	30000	180000	×	×	100
	LF	60000	0	0	30000	180000	×	×	100
2nd	CC	55000	0	9000	30000	100000	×	×	98
	LF	55000	0	9000	30000	140000	×	×	99
3rd	CC	60000	300	0	30000	140000	×	×	100
	LF	60000	300	0	30000	140000	×	×	100
4th	CC	40000	900	9000	20000	100,000	×	×	93
	LF	55000	1000	9000	20000	100,000	×	×	97
5th	CC	55000	0	0	15000	180,000	×	×	100
	LF	55000	0	0	15000	180,000	×	×	100
6th	CC	50000	0	9000	10000	100,000	×	×	97
	LF	50000	0	9000	10000	140,000	×	×	99
7th	CC	55000	400	0	20000	140,000	×	×	100
	LF	55000	500	0	20000	140,000	×	×	100
8th	CC	35000	900	9000	10000	100,000	×	×	92
	LF	50000	1000	9000	10000	100,000	×	×	95
9th	CC	30000	0	0	×	×	25925564	42565188	72
	LF	30000	0	0	×	×	25925564	42565188	72
10th	CC	20000	0	9000	×	×	270001138	22533684	63
	LF	20000	0	9000	×	×	270001138	22533684	63
11th	**CC**	**35000**	**600**	**0**	×	×	**22582148**	**55031308**	**80**
	LF	**35000**	**600**	**0**	×	×	**22582148**	**55031308**	**80**
12th	CC	20000	1000	9000	×	×	21562420	25854966	73
	LF	20000	1000	9000	×	×	21562420	25854966	73

aims such as charging the storage or serving the deferrable load are the responsibility of the *RETs* sources. However, it may allow the generator production to sell the power to the grid if economically it is advantageous. On the other hand, in The *CC* strategy, A generator operates at full output power when needed to serve the primary load. once the demand of the specified primary load is met, the surplus electrical production goes towards the secondary objectives such as serving the deferrable load, charging the storage bank, etc. In the *CC* strategy, generators will not be allowed to produce excess electricity just for dumping. Surplus power generated must be utilized in HOMER PRO so that, it can operate above the levels desired to meet the primary load demand. HOMER dispatch the controllable power sources (generators, storage bank, and grid) in simulation by a two-step process in *CC* strategy. First, HOMER selects the optimal combination of sources of energy to serve the primary load and the thermal load at the least total cost, while satisfying the operating reserve requirement. Secondly, it ramps up the production of each generator in the most optimal combination to its full rated capacity, or as close as possible without causing excess electricity.

C. DESCRIPTION REGARDING KEY PARAMETERS AND SYSTEM CONFIGURATION USED FOR SIMULATION

1) INFLATION RATES AND NOMINAL DISCOUNT FACTOR

As per the historic inflation data of india, provided by tri-ami media [113], an inflation rate of 5.71 % is considered annually over the project lifetime. Based on *CERC* [101], 10.70 % has been considered as the discount factor for all the renewable energy technologies.

2) PROJECT LIFETIME

A higher project lifetime has several issues considering technical and economic aspects while designing a hybrid energy system based on yearly load growth which is also pointed

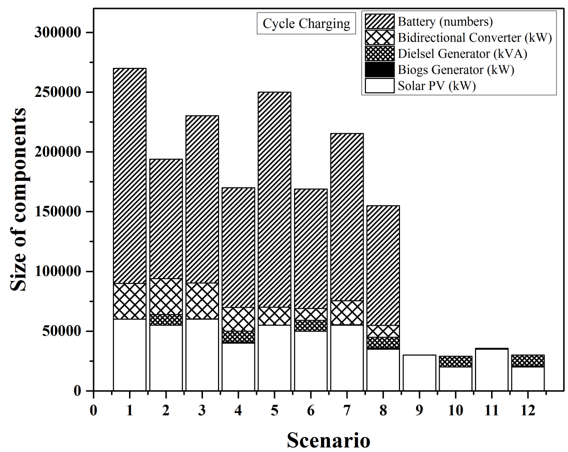


FIGURE 8. Sizing of various components in 12 scenarios in cycle charging dispatch.

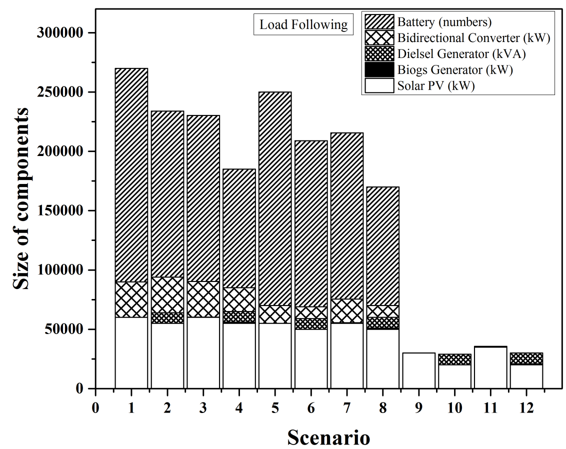


FIGURE 9. Sizing of various components in 12 scenarios in load following dispatch.

out in the introduction section. Also, the dependency on the weather for *RETs*, decrease in their efficiency on an annual basis, the fluctuations in their *O & M* cost, etc. Are a few more possible causes. Due to all these issues, 15 years is assumed as project life in this analysis.

3) SYSTEM FIXED COST

As mentioned in the introduction section, the capital cost of technologies which are considered in this analysis accounts for all type of cost involved and has been included with specific *RETs* as per the prescribed rate by *CERC* [101]. However, the capital and *O & M* cost of Barc's nisarg-runa biogas plant is included in the system fixed costs. upon discussion with the people from industry and potential project investors, INR 500000 is also added up to fixed *O&M* cost which accounts for small maintenance. the system fixed capital cost is the cost that occurs at the start of the project with no effect on size or architecture of the system [105], [109]. The system *O&M* cost is the recurring annual cost that occurs regardless of the size or architecture of the power system [105], [109].

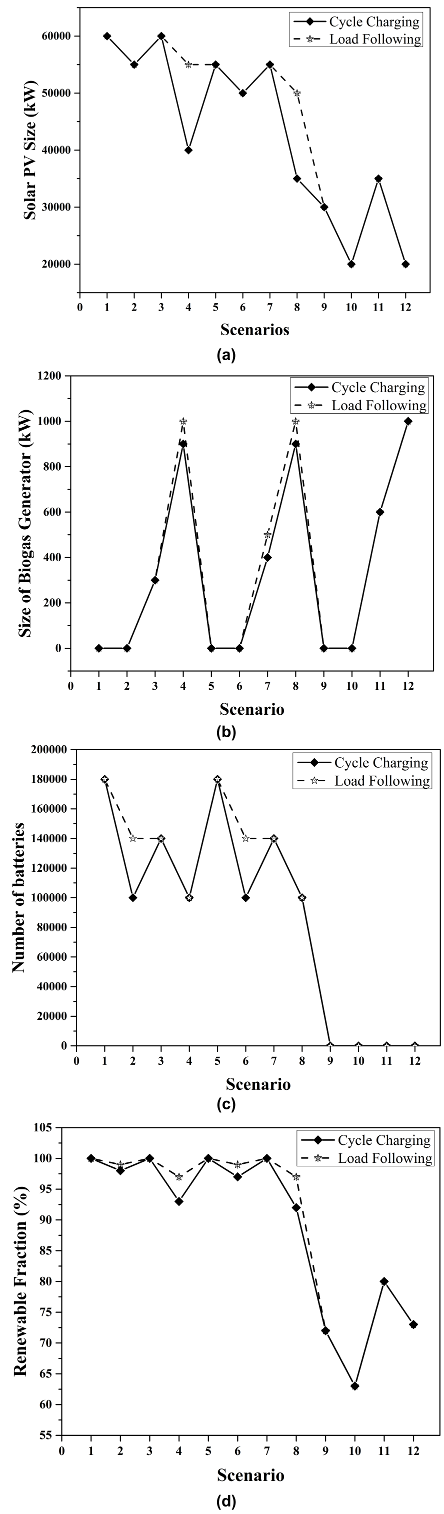


FIGURE 10. Comparative illustration of sizing of SPV, BG, LAB and RF in 12 microgrid scenarios (a) SPV Size in 12 scenarios with CC and LF dispatch (b) BG Size in 12 scenarios with CC and LF dispatch (c) Battery size in 12 scenarios with CC and LF dispatch (d) Renewable fraction Size in 12 scenarios with CC and LF dispatch.

the system fixed cost affects the net present cost (*NPC*) of all system configurations in the search space by the same amount as it has no effect on the system rankings [105], [109].

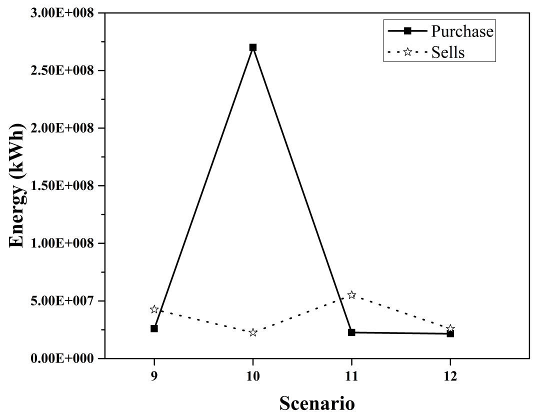


FIGURE 11. Total energy purchase and sold to the grid.

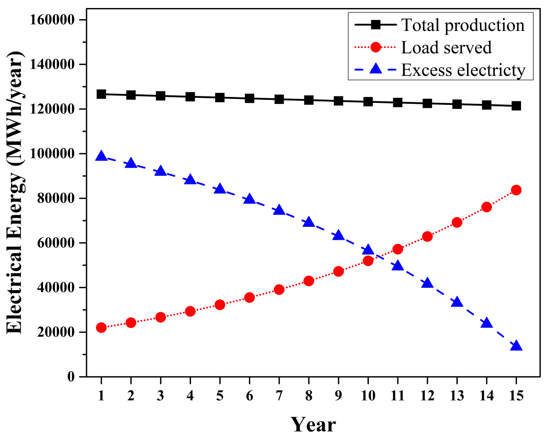


FIGURE 12. Total energy production, load served and excess electricity generation for the 1st microgrid scenario in CC dispatch.

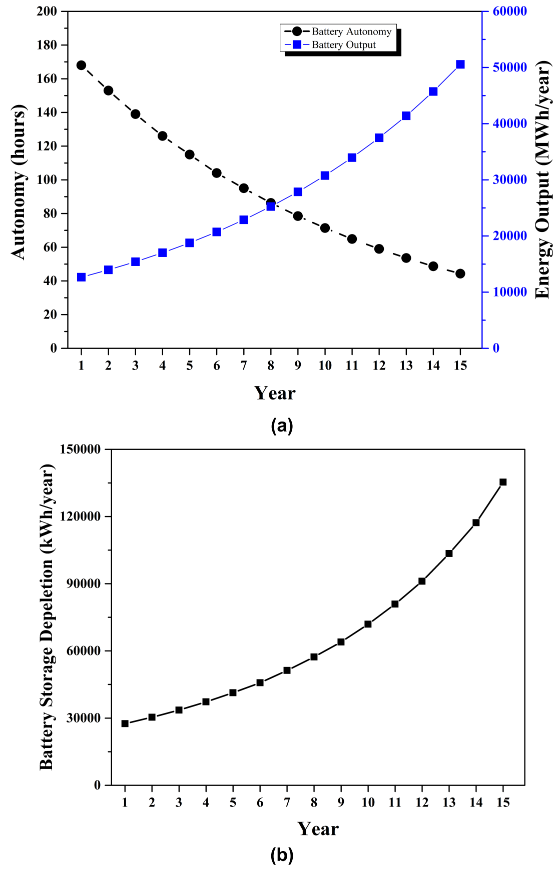


FIGURE 13. Battery parameter profiles for the 1st microgrid scenario in CC dispatch (a) Battery autonomy and energy output over the assumed project life (b) Battery yearly energy storage depletion over the project life.

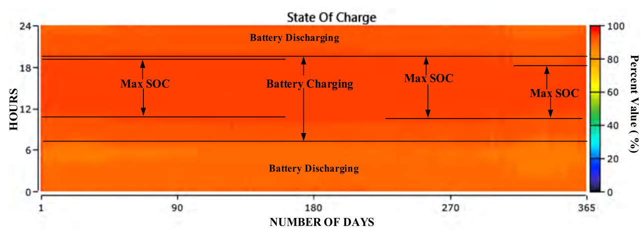


FIGURE 14. Battery SOC profiles for the 1st microgrid scenario in CC dispatch during first (1st) year of operation.

4) SYSTEM CONFIGURATION WITH VARIOUS MICROGRID SCENARIOS

A total of 12 microgrid scenarios in off-grid and grid connected mode are taken up for the technical and financial evaluation. the details of various microgrid scenarios along with their architecture adopted for the assessment is given in *Appendix (Table 5)* [28], [114].

V. SIMULATION RESULTS

As outlined in the previous section, using the specifications of the various components detailed in Table 2 and considering the 12 microgrid design scenarios which are specified in *(Appendix, Table 5*), simulations are performed. Results obtained are presented as follows.

A. TECHNICAL RESULTS

The optimal size of various components for various scenarios are given in Table 3. A graphical illustration of the optimal sizing of the different components in all the 12 microgrid scenarios considered under *CC* dispatch strategy is shown in Figure 8. Figure 9 shows the component sizing of various scenarios when the simulations are carried out with *LF* dispatch algorithm.

It is observed from the Figure 8, Figure 9 and Table 3 that in the off-grid scenarios (1^{st}-4^{th}) when *SPV* is connected on the AC bus, scenario 1 (only *SPV* as generation unit) has the highest number of *LAB* and *SPV* followed by 3^{rd} scenario (with *SPV* and *BG* as power source) in *CC* as well as *LF* dispatch strategy. Also, both the scenarios have the 100% renewable fraction. Even when *SPV* is connected to the DC bus in the off-grid scenarios (5^{th}-8^{th}), the highest number of *LAB* and *SPV* is in 5^{th} scenario (only *SPV* as generation unit) followed by 7^{th} scenario (with *SPV* and *BG* as a

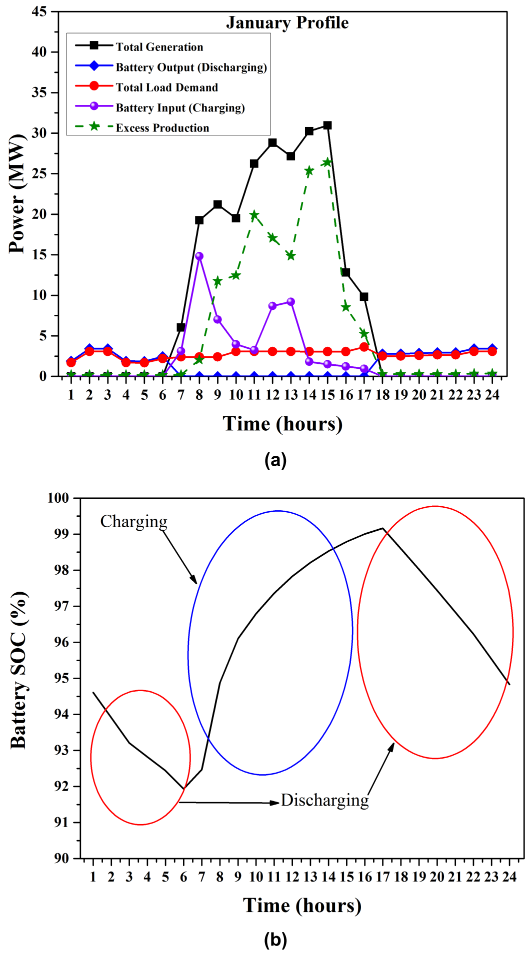


FIGURE 15. **Daily averages of power profile and battery SOC for January month in CC dispatch for 1st microgrid scenario during 1st year of operation (a) Average power profiles on hourly basis (b) Battery average SOC profile on the hourly basis.**

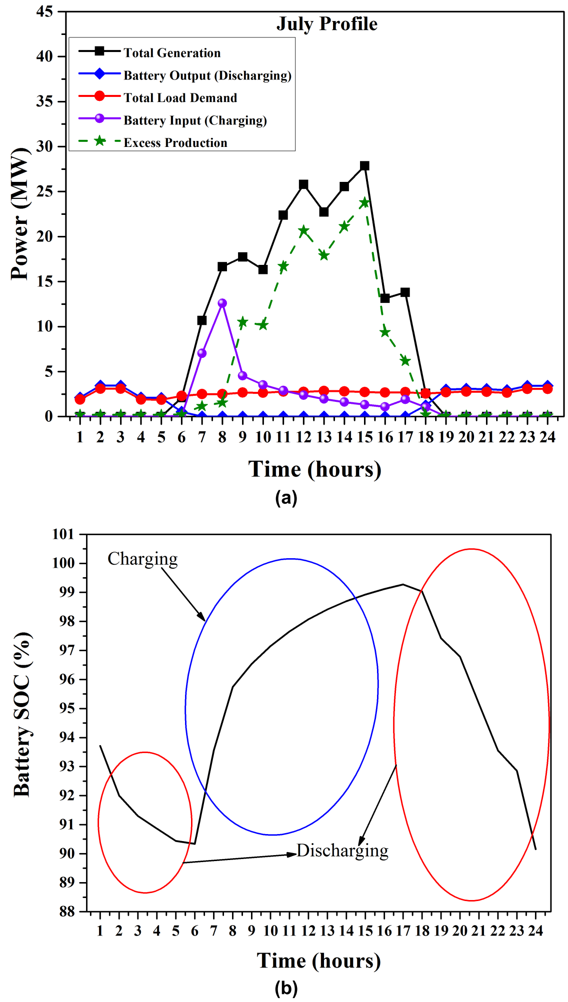


FIGURE 16. **Daily averages of power profile and battery SOC for July month in CC dispatch for 1st microgrid scenario during 1st year of operation (a) Average power profiles on hourly basis (b) Battery average SOC profile on the hourly basis.**

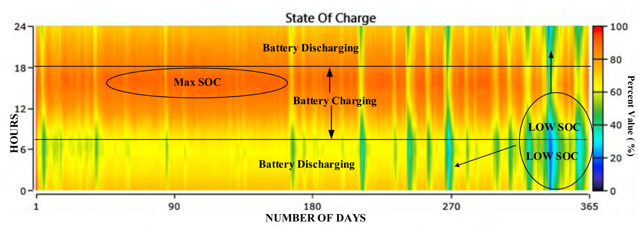


FIGURE 17. **Battery SOC profiles for the 1st microgrid scenario in CC dispatch during final year (15th) of operation.**

power source). In both dispatch algorithms, a slight deviation is observed in the size of the *LAB, SPV, BG,* and *% RF* when all the microgrid design scenarios (1st-12th) are considered. However, in both dispatch strategies in grid-connected scenarios (9th-12th), the size of components (*SPV, BG*, and *DG*) and the electricity purchase and sells to grid along with *% RF* remains the same. A comparative illustration regarding the difference in the size of *LAB, SPV, BG* and *% RF* with *CC* and *LF* as microgrid system controllers has been shown in Figure 10 (a, b, c, and d).

In a grid-connected architecture, 11th scenario constitutes the highest renewable fraction with *SPV* size of 35000 kW and *BG* of 600 kW ratings with a grid electricity purchase of 22582148 kWh and sell back of 55031308 kWh. Figure 11 illustrates the electricity purchase from the grid and sold back to the grid. In 10th microgrid scenario, the energy purchase from the grid is significantly higher due to low component size (*SPV* of 2000 kW and *DG* of 9000 kVA) as compared to the other grid microgrid scenarios. All the energy systems evaluated are capable of providing 24 hours of electricity for the project lifetime with yearly electrical load growth. As an example, the critical multiyear based results (total production, load served, excess electricity production, converter profiles and battery profiles) of 1st scenario in *CC* dispatch strategy are presented in Figures 12-21. Figure 12 shows the total energy produced, load served and excess electricity on a yearly basis for the assumed project lifetime.

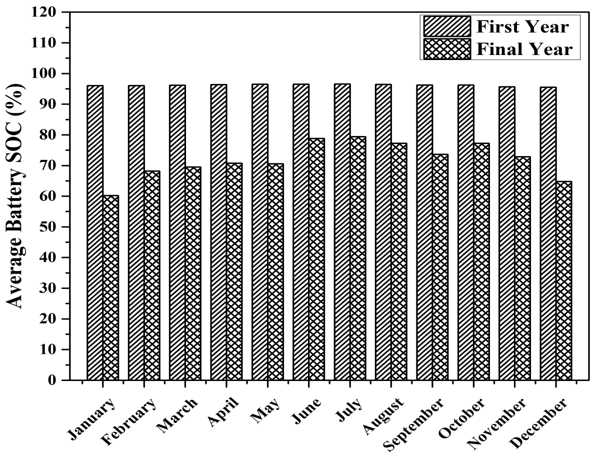


FIGURE 18. Average monthly battery SOC profiles for the 1st microgrid scenario in CC dispatch during the first and final year of operation.

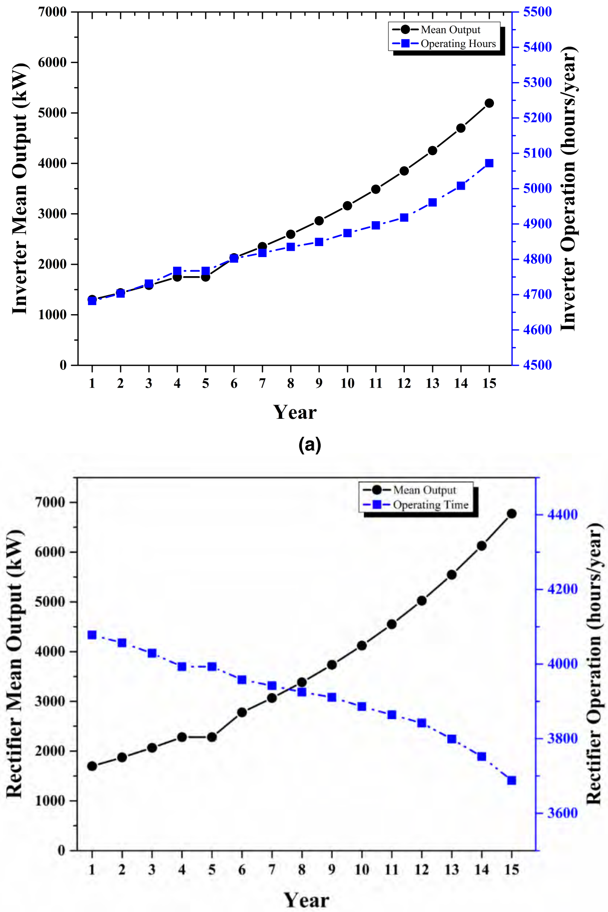


FIGURE 19. System converter profile for the 1st microgrid scenario in CC dispatch during the project life (a) Inverter mean output along with hourly operation over the years (b) Rectifier mean output along with hourly operation over the years.

The average electrical energy production remains almost same with a slight variation (approximately 126642 MWh for 1st year to 121425 MWh for the 15th year) with a mean output of 14.45 MW over the years as illustrated in Figure12. However, the average electrical energy required to serve the primary load increases approximately from 22038 MWh in the first year to 83690 MWh for the last year. However, around 98508 MWh (77 %) of excess electricity generation during the first year is observed which declines to 13470 MWh (11%) by the final year of project lifetime shown in Figure 12. Figure 13 (a, b) illustrates the battery autonomy, energy output, and its depletion over the project life (15 years assumed in this study). The battery autonomy duration decreases on a yearly basis from 168 hours to 44.3 hours for the assumed project life as shown in Figure 13 (a).

As the load demand increases on a yearly basis, the energy output from the battery also increases to serve the increasing load over the years which can be observed from Figure 13 (a). With a span of time, the storage depletion also increases from 27511 kWh in the first year to 135327 kWh in the final year of the project lifetime illustrated in Figure 13 (b).

The state of charge (*SOC*) of the battery for 365 days on an hourly basis during 1st year of operation in CC dispatch strategy is illustrated in Figure 14. From Figure 14 it can be observed that battery discharges during early morning hours from 0100 hours to 0600 hour and evening hours between 1900 hours to 2400 hours respectively to meet the load demand in the absence of the power output from the *SPV* in the 1st microgrid scenario. Also, the battery *SOC* is maintained on an average above 90 % throughout the year as shown in Figure 14. A typical 24- hour power and *SOC* profile of daily averages for the month of January (winter season) in *CC* dispatch for 1st microgrid scenario is shown in Figure 15 (a, b). It can be observed from Figure 15 (a, b) that, during the morning (0100 – 0600) and evening (1900-2400) hours the load demand is met by discharging the battery in the absence of power generation from *SPV*. Once the power is available from *RETs* (*SPV* in this case) from 0600 – 1800 hours, first the load demand is met and then balance power is send to batteries to maintain its *SOC* as shown in Figure 16 (a, b). During the January month, on an average the batteries *SOC* varies between 92-99 % as illustrated in Figure 15 (b).

Similarly, Figure 16 (a, b) exemplifies the profiles for the month of July (summer season). A small variation in the power and *SOC* profile in January and June months can be observed. During, January the *SPV* output is present between 0600 hours to 1800 hours but in July the *SPV* output is from 0500 hours to 1900 hours which is solely due to the seasonal variations shown in Figure 15 (a) and Figure 16 (a) respectively.

In case the load demand is met, and batteries cannot absorb more power, then the surplus electricity (excess electricity) must be dumped. However, the amount of excess power production can be observed in both the cases (January and July) with very slight variations shown in Figure 15 (a) and Figure 16 (a). During the first year of operation, the excess electricity generation is more (around 77 %) as shown

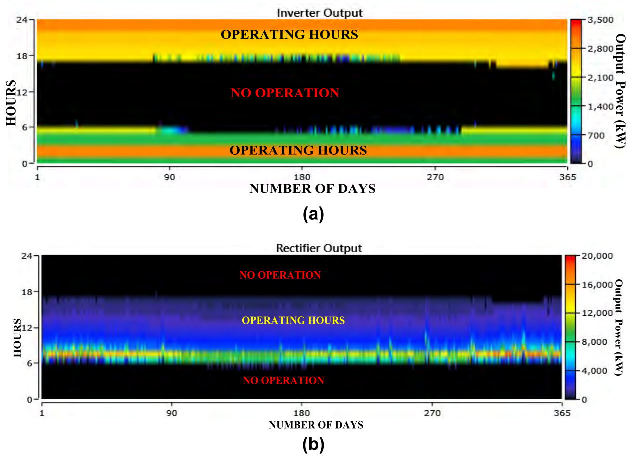


FIGURE 20. System converter profile for the 1st microgrid scenario in CC dispatch during the first (1st) year of operation (a) Inverter output profile on an hourly basis during the first year (b) Rectifier output profile on an hourly basis during the first year.

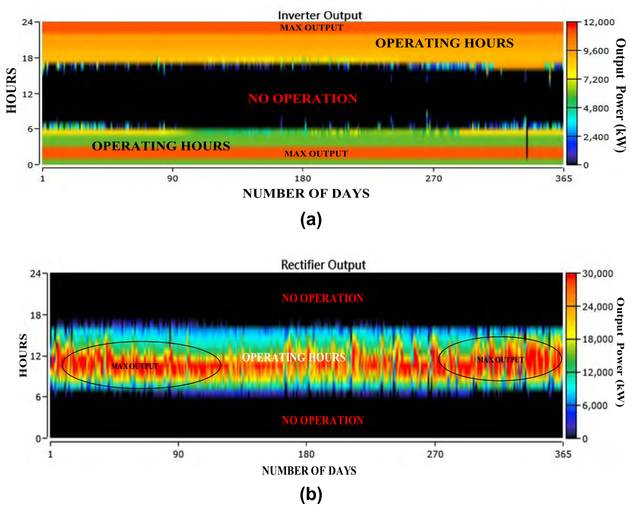


FIGURE 21. System converter profile for the 1st microgrid scenario in CC dispatch during the final (15th) year of operation (a) Inverter output profile on an hourly basis during the final year (b) Rectifier output profile on an hourly basis during the final year.

in Figure 12. During the 1st year of operation, the *SOC* of the battery is maintained at approximately above 90 % throughout the year shown in Figure 14 and Figure 18. However, during the final year of operation, a lot of variation in battery *SOC* can be observed as shown in Figure 17. Figure 18 depicts the average monthly battery storage *SOC* profile for the first and final year of operation in 1st microgrid scenario.

The battery *SOC* on an average is usually between 65-80 % in the final year of operation from February to November months (Figure 17 and 18). However, during December the battery *SOC* some days reaches below 35 % (daily variations) during early morning hours but maintaining a monthly average of 60 % illustrated in Figure 18. In the final year of operation as the load demand increase, the *SOC* of batteries attain lower value with many variations as compared

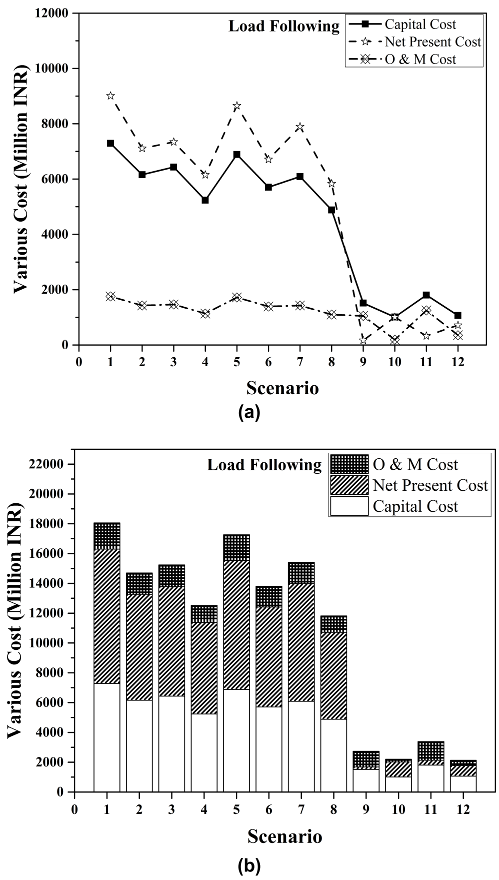


FIGURE 22. Various cost of 12 microgrid scenarios in load following dispatch. (a) Individual representation of *CPC, NPC* and *O & M* for optimal energy system (b) Total cost of systems for optimal energy systems.

to the first year of operation illustrated in Figure 17 and 18, and the amount of excess electricity declines to about 11 % in the final year for the 1st microgrid scenario. Bidirectional converter (inverter and rectifier) mean output and operating hours over the project lifetime on a yearly basis have been shown in Figure 19 (a) and (b) respectively. The working hours and mean output of the inverter increases correspondingly over the years to manage the optimum power flow from the source to load and to storage, as illustrated in Fig. 19 (a). The inverter mean output increases from 1301 kW in the first year to 5194 kW in the last year along with its operating hours (from 4682 hours in first year to 5072 hours final year).

The inverter mostly operates to maintain a steady flow of power to serve the load during early morning hours (2400 to 0700) and evening hours (1800-2300) by discharging the stored energy from battery in the absence of power output from *SPV* as shown in Figure 20 (a) during first year and Figure 21 (a) for the final year of project lifetime respectively. The rectifier output also increases from 1698 kW during the first year to 6733 kW in the final year with average operating hours of 3914 per year through the project lifetime as illustrated in Figure 19 (b). The rectifier operating hours is during the daytime from 0700 to 1700 as

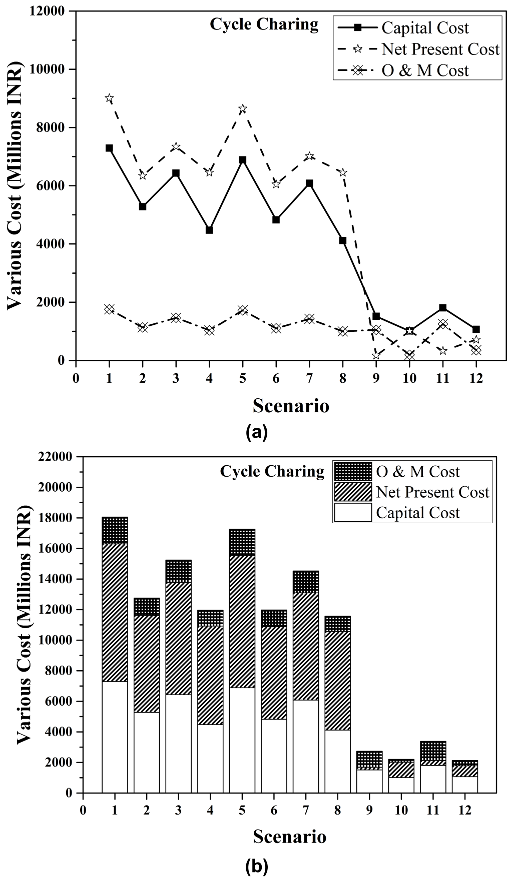


FIGURE 23. Various cost of 12 microgrid scenarios in cycle charging dispatch. (a) Individual representation of *CPC, NPC* and *O & M* for optimal energy system (b) Total cost of systems for optimal energy systems .

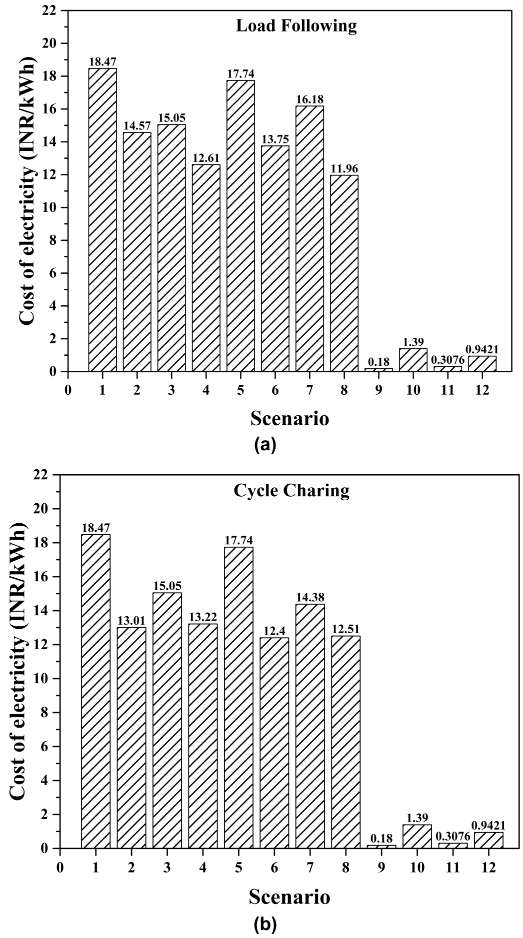


FIGURE 24. Levelized cost of electricity for 12 microgrid scenarios (a) *LCOE* of microgrid scenarios when optimized using load following dispatch (b) *LCOE* of microgrid scenarios when optimized using cycle charging dispatch.

observed from Figure 20 (b) and Figure 21 (b) utilized mostly for maintaining the battery *SOC*. The output profiles of the system converter changes as illustrated in Figure 20 and Figure 21 during the first and final year of operation. The optimum flow of power between the source to load and then to storage in a cost-effective manner via bidirectional converter is maintained by the system controller or energy management system (in this study *CC* and *LF* strategies). The multiyear electrical parametric results (*directly obtained in PNG format from HOMER PRO*) for other scenarios ($2^{nd} - 12^{th}$) in *CC* and *LF* dispatch has been given in the *supplementary material (section A)*.

B. ECONOMIC RESULTS

Table 4 presents the summary of the total cost of the optimized microgrid scenarios incurred over the project lifetime in the *LF* and *CC* dispatch strategy. The *NPC* in the case of off-grid scenarios ($1^{st} - 8^{th}$) varies from 6450 to 9009 million INR for *CC* dispatch and 5835 to 9009 million INR for *LF* dispatch respectively. This variation can also be observed in the *CPC* (4119-7290 million INR for *CC* and 4882-7290 million INR for *LF*), *O & M* cost (998-1756 million INR for *CC* and 1100-1756 million INR for *LF*), fuel cost (18-755 million INR for *CC* and 3-47 million INR for *LF*) and *LCOE* (12.51-18.47 INR/kWh for *CC* and 11.96-18.47 INR/kWh for *LF*) respectively. This variation in cost is solely based on the calculation of component sizes and prices in *CC* and *LF* strategy by HOMER optimizer. Only for the 1^{st} and 5^{th} off-grid scenario the *CPC, NPC, O & M* cost and *LCOE* are same for both *LF* and *CC* dispatch due to the similar component sizes obtained after simulation as illustrated in Table 3. It is also observed from the Table 4 that, the *CPC, NPC, O & M* cost and *LCOE* are same for the grid-connected microgrid scenarios ($9^{th} - 12^{th}$) in both the dispatch (*LF* and *CC*). The annualized cost is detailed in the *attached supplementary material in section B*. Figures 22 (a, b) and 23 (a, b) illustrate the various cost (*CPC, NPC, O & M*) incurred in obtaining the optimal sizes of the components in 12 microgrid scenarios using both the dispatch strategy (*LF* and *CC*). Out of 12 microgrid scenarios, 1^{st} microgrid scenario is the most expensive option with a very high *CPC* of 7290 million INR and a *NPC* of 9009 million INR followed by the 5^{th} microgrid scenario

TABLE 4. Various total cost of the optimized energy systems in different microgrid scenarios.

Microgrid Design Scenario	Dispatch Algorithm	*CPC* (Millions INR)	*NPC* (Millions INR)	*O & M* (Millions INR)	Fuel Cost (Millions INR)	*LCOE* (INR/kWh)
1st	CC	7290	9009	1756	0	18.47
	LF	7290	9009	1756	0	18.47
2nd	CC	5278	6344	1134	18	13.01
	LF	6158	7110	1427	3	14.57
3rd	CC	6432	7344	1465	0	15.05
	LF	6432	7340	1465	0	15.05
4th	CC	4471	6450	1034	662	13.22
	LF	5234	6150	1136	8	12.61
5th	CC	6888	8653	1719	0	17.74
	LF	6888	8653	1719	0	17.74
6th	CC	4825	6051	1101	283	12.40
	LF	5705	6709	1392	47	13.75
7th	CC	6084	7013	1428	0	14.38
	LF	6089	7894	1428	0	16.18
8th	CC	4119	6450	998	755	12.51
	LF	4882	5835	1100	15	11.96
9th	CC	1515	169	1050	0	0.18
	LF	1515	169	1050	0	0.18
10th	CC	1010	1004	191	0	1.39
	LF	1010	1004	191	0	1.39
11th	**CC**	**1804**	**327**	**1251**	**0**	**0.31**
	LF	**1804**	**327**	**1251**	**0**	**0.31**
12th	CC	1066	714	353	0	0.94
	LF	1066	714	353	0	0.94

having a *CPC* of 6888 million INR and *NPC* of 8653 million INR in both the dispatch (*LF* and *CC*) respectively.

Even the *LCOE* for the 1st microgrid scenario (18.47 INR/kWh) is highest followed by the 5th option (17.74 INR/kWh) when compared to all scenarios in *LF* and *CC* dispatch. Figure 24 (a, b) shows the cost of electricity for all the scenarios in *LF* and *CC* dispatch.

A comparative representation of the scenarios involving various costs in both the dispatch (*LF* and *CC*) has been presented in Figure 25 (a-d). The *LCOE* of the grid scenarios (9th − 12th) is very low in comparison to all the off-grid scenarios (1st − 8th) as illustrated in Figure 24 (a, b) and Figure 25 (d) respectively. The 9th microgrid scenario has the lowest *LCOE* (0.18 INR/kWh) followed with 11th (0.3076 INR/kWh) and 12th (0.9421 INR/kWh) in comparison to all the off-grid microgrid scenarios. Considering both the technical and economic results for the optimal solution for 12 microgrid scenarios, 4th and 8th microgrid scenarios in off-grid mode have best optimal solutions with a higher renewable fraction (93-97 % for 4th and 92-95 % for 8th) and 11th scenario in grid-connected mode with 80 % renewable fraction.

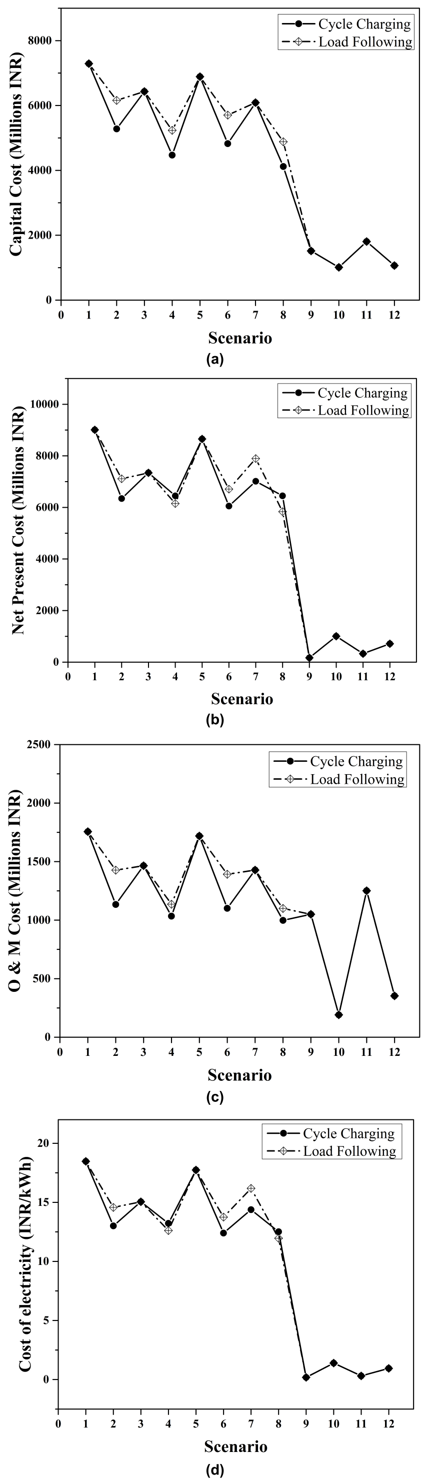


FIGURE 25. Comparative illustrations of various cost for optimal systems in 12 microgrid scenarios (a) *CPC* of microgrid scenarios when optimized using *CC* and *LF* dispatch (b) *NPC* of microgrid scenarios when optimized using *CC* and *LF* dispatch (c) *O & M of* microgrid scenarios when optimized using *CC* and *LF* dispatch (d) *LCOE* of microgrid scenarios when optimized using *CC* and *LF* dispatch.

The *NPC* of 4th and 8th is lowest when compared to the off-grid scenario (1st – 8th), however, when comparing all the microgrid scenarios (1st – 12th), the 9th scenario has the least *NPC* and *LCOE* respectively. However, the renewable fraction (*RF*), in this case, is 72 % which is less when compared to other microgrid scenarios (1st – 8th in isolated and 11th-12th in the grid-connected system). Excess electrical production is observed till the 9th year of project lifetime as shown in Fig. 12 for the 1st scenario. Similarly, excess productions are also observed in the case of all other off-grid microgrid scenarios (2nd-8th) shown in the technical results given in the *supplementary material (Section B).* In grid-connected scenarios with *DGs* (10th and 12th), the load demand is met either by *SPV* with grid electricity or *SPV* and *BG* with grid power as it is more economical to meet the demand without operating the *DG* (*technical results profiles in the supplementary material*). Hence, for isolated solutions 4th and 8th scenarios with *SPV, BG, DG* and *LAB* are better solutions with a green microgrid perspective with a higher share of renewable fraction and utilization of locally available resources. Overall, 11th scenario in grid-connected mode is excellent choice considering low cost and a significant *RF* share (80 %) along with higher excess power selling to the grid with the optimum exploitation of *SPV* and *BG*.

VI. CONCLUSIONS

The primary purpose of this study is to outline the research gaps present in the existing literature on feasibility evaluation and design of microgrids based on the renewable energy technologies. Moreover, in this work, a hybrid energy system based on *SPV*, *BG*, *DG* and taking 12 microgrid design scenarios (isolated and grid connected) considering an account of yearly electrical load growth in two dispatch strategies (*LF* and *CC*) with a case study for a real physical location (*IIT GHY*) is implemented. The biogas resource from the kitchen waste of the *IIT GHY* is utilized for electricity generation using *BG* which proves to be an efficient waste management strategy. The results obtained illustrate that, in off-grid scenario (1st-8th), the *NPC* (5835 million INR) and *LCOE* (11.96 INR/kWh) is lowest for the 8th scenario with *LF* dispatch algorithm. But, in *CC* dispatch strategy the *NPC* (6450 million INR) and *LCOE* (12.51 INR/kWh) of the 8th scenario becomes higher as compared to *LF*. The *RF*of the 8th scenario is more in *LF* (95 %) when compared to *CC* (92 %) dispatch strategy. For grid-connected scenarios (9th-12th), 9th scenario has the lowest *NPC* (169 million INR) and *LCOE* (0.18 INR/kWh) followed by 11th scenario with a *NPC* of 327 million INR and *LCOE* of 0.31 INR/kWh respectively in both the dispatch strategy (*LF* and *CC*). However, the *RF* of 11th scenario (80 %) is more in comparison to 9th scenario (72 %). Also, the amount of energy sold back to the grid is more for 11th scenario (55031308 kWh) as compared to the 9th scenario (42565188 kWh). The system dispatch algorithms (*LF* and *CC*) gives similar results for all the grid-connected scenarios (9th-12th) as illustrated in technical and financial results. However, variations in component sizes (technical results) and cost (economic results) is observed in the results obtained for the off-grid scenarios (1st-8th) in *CC* and *LF*. In all the off-grid energy scenarios

TABLE 5. **Various microgrid design scenarios in different architecture.**

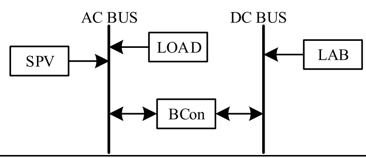
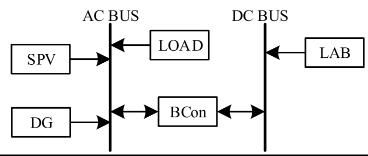
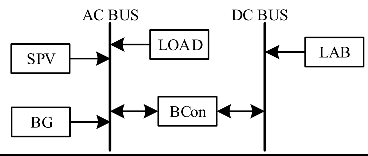
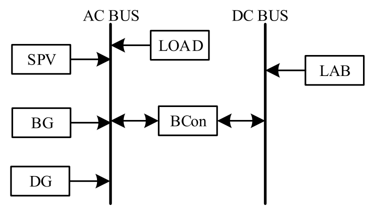
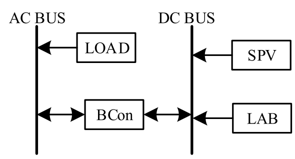
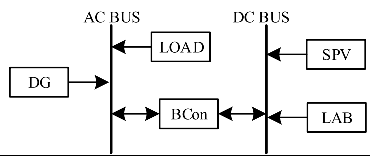
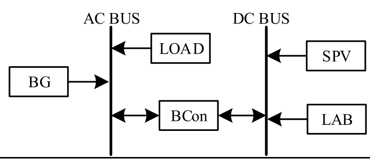
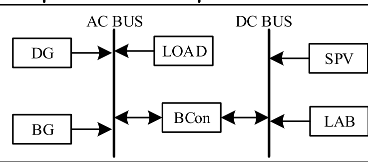
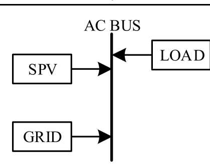
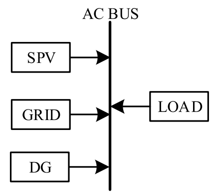
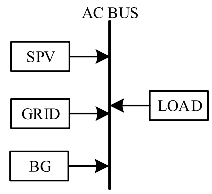
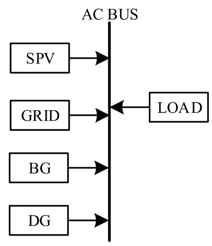
Microgrid Design Scenario	Components						Configuration	Microgrid Architecture
	SPV	*BG*	*DG*	*BCon.*	*LAB*	*Grid*		
1^{St}	✓	✗	✗	✓	✓	✗	Off-grid	
2^{nd}	✓	✗	✓	✓	✓	✗	Off-grid	
3^{rd}	✓	✓	✗	✓	✓	✗	Off-grid	
4^{th}	✓	✓	✓	✓	✓	✗	Off-grid	
5^{th}	✓	✗	✗	✓	✓	✗	Off-grid	
6^{th}	✓	✗	✓	✓	✓	✗	Off-grid	
7^{th}	✓	✓	✗	✓	✓	✗	Off-grid	
8^{th}	✓	✓	✓	✓	✓	✗	Off-grid	
9^{t}	✓	✗	✗	✗	✗	✓	With Grid	

TABLE 5. ***(Continued.)*** **Various microgrid design scenarios in different architecture.**

10^{th}	✓	✓	×	×	×	✓	With Grid	
11^{th}	✓	×	✓	×	×	✓	With Grid	
12^{th}	✓	✓	✓	×	×	✓	With Grid	

the excess electricity production is observed from the results till the 9^{th} year of project lifetime. Hence grid-connected microgrid solutions must be preferred which can sell back the excess energy production to the grid. Based on the results, as the fraction of electricity generated from *BG* is around 2-3%, it is suggested to use the biogas produced for cooking and heating purpose rather than for the production of electricity. This study not only points out the importance of taking into account the future load growth projections but also suitable dispatch strategies while designing renewable energy systems which will undoubtedly help in avoiding technical as well as financial errors. In the future works, the design scenarios can be extended to a component level design while considering weather uncertainties and change in climatic conditions.

APPENDIX

See Table 5.

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ABHISHEK KUMAR (GS'11) received the B.Tech. degree in electrical & electronics engineering from Pondicherry Central University, India, in 2009, and the M.Tech. degree in power system from NERIST Deemed University, India, in 2012. He is currently pursuing the Ph.D. degree with the College of Electrical Engineering, Zhejiang University, China. He has also served as an Assistant Professor with NIT, Arunachal Pradesh, for two years from 2012 to 2014. His research interest includes sustainable rural electrification systems, microgrids, smart grids, renewable energy systems, power electronics & its industrial applications, power system, and optimization and application of decision analysis in energy planning. He is a member of IET, U.K.

ARVIND R. SINGH received the B.E. degree in electrical engineering from Walchand College of Engineering (Govt. Autonomous Institute), Sangli, India, in 2009, the M.Tech. degree in electrical power system from the College of Engineering (Govt. Autonomous Institute), Pune, India, in 2011, and the Ph.D. degree in electrical engineering from the Visvesvaraya National Institute of Technology, Nagpur, India, in 2017. He is currently a Post-Doctoral Research Fellow with the University of Pretoria, Pretoria, South Africa. His area of research includes power system protection, power system compensation, smart grid, microgrid and renewable energy generation, optimization, integration, and soft computing applications.

YAN DENG received the B.E.E. degree in electrical engineering from Zhejiang University, Hangzhou, China, in 1994, and the Ph.D. degree in power electronics and electric drives from the College of Electrical Engineering, Zhejiang University, in 2000. Since 2000, he has been a Faculty Member with Zhejiang University, teaching and conducting research on power electronics. He is currently a Professor with Zhejiang University. His research interests include topologies and control for switch-mode power conversion.

XIANGNING HE (M'95–SM'96–F'10) received the B.Sc. and M.Sc. degrees in automation engineering from the Nanjing University of Aeronautics and Astronautics, Nanjing, China, in 1982 and 1985, respectively, and the Ph.D. degree in electrical engineering from Zhejiang University, Hangzhou, China, in 1989. From 1989 to 1991, he was a Lecturer with Zhejiang University. In 1991, he received a Fellowship from the Royal Society of U.K., and conducted research at Heriot-Watt University, Edinburgh, U.K., as a Post-Doctoral Research Fellow for two years. In 1994, he joined Zhejiang University as an Associate Professor, where he has been a Full Professor since 1996. He is currently the Vice Dean of the College of Electrical Engineering, Zhejiang University. He has published over 280 papers and holds 22 patents. His research interests include power electronics and their industrial applications.

PRAVEEN KUMAR (SM'16) has core expertise of electrical engineering industry and academics. He was a Team Leader of Hybrid Systems Group, Drive Trains Innovation B.V., The Netherlands; a Co-Founder of elmoCAD GmbH, Germany; and a Development Engineer at Trimeric GmbH, Germany, and Durr AG, Germany. He is currently a Professor with the Department of Electronics and Electrical Engineering, IIT Guwahati, Guwahati. His research activities are in optimization of electrical motors and drives; State of the art algorithm development for multi-objective optimization and simulation for power system and smart grid applications; and design of electrical motors and actuators using finite element methods; besides years long hands on experience with analytical modeling of electrical motors for rapid simulation.

RAMESH C. BANSAL (SM'03) has more than 25 years' experience in teaching, research, and industry. He was with the University of Queensland, Australia, the University of the South Pacific, Fiji, the Birla Institute of Technology and Science, Pilani, India, and the Civil Construction Wing of All-India Radio. He has with Powerlink, an Australian government-owned corporation responsible for Queensland's high-voltage electricity transmission network. He has significant industrial experience involved with power utilities, includes NTPC (A 40 GW Indian Power Generation Company) and ESKOM (Generation, Transmission & Distribution Company in Africa). He is currently a Professor and a Group Head (Power) with the Department of Electrical, Electronic and Computer Engineering, University of Pretoria. He has published over 275 journal articles, presented papers at conferences, and has contributed to books and chapters in books. He has supervised 18 Ph.D. students and currently supervising 10 Ph.D. students. His diversified research interests include in the areas of renewable energy and conventional power systems, include wind, photovoltaics, hybrid power systems, distributed generation, grid integration of renewable energy, power systems analysis, smart grid, flexible ac transmission systems, and power quality. He is a Fellow and a Chartered Engineer of the Institution of Engineering and Technology, U.K., a fellow of the Engineers Australia, and a fellow of the Institution of Engineers, India. He is an Editor of the highly regarded journals, *IET Renewable Power Generation* (regional editor for Africa) and *Electric Power Components and Systems*.