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Optimal resource integration in a decentralized renewable energy system: Assessment of the existing system and simulation for its expansion

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ABSTRACT

Micro-grids are actively employed for rural electrification along with integrated renewable energy systems in developing countries. For determining their optimal configurations, it is often challenging in obtaining accurate input data, particularly prospective electricity loads and local renewable resource availability. In this study, the configuration of the off-grid 120 kWp PV system in West Bengal, India is reassessed by using the optimization software, HOMER. With an assumption that excess biomass resources would be available as a result of successful introduction of fuel-saving devices such as solar cookers, a PV–biomass–battery system, which consists of 30 kW PV array and 20 kW biomass gasification-based power plant (BGPP), turns out to be the most economically feasible option. Compared with the actual system, the net present cost (NPC) and cost of electricity (COE) are significantly lowered. Furthermore, in order to verify effectiveness of "phased approach" for developing the off-grid renewable energy system, which has been proposed in the authors' previous study, the system expansion process is simulated by HOMER according to three different load growth scenarios. It is found from the simulation that adjustment of the system size becomes possible with more accurate load estimation at the time of expansion, which may lead to lower operation and maintenance (O&M) costs and COE. As a result of the increased level of tariff revenue from additional consumers, the expansion process would provide an opportunity for enhancing community welfare and financial viability of the project.

Introduction

Decentralized renewable energy systems have been promoted for the electrification of remote areas when grid extension is not economically feasible (Hiremath et al., 2009; Kaundinya et al., 2009; Nouni et al., 2008; Sinha and Kandpal, 1991). For providing electricity to somewhat densely populated remote areas of India, decentralized renewable energy systems providing electricity to households via micro-grids have been considered as one of the economically feasible options. The micro-grid systems also offer the possibility of integrating various locally available renewable resources to establish relatively larger power generation capacity systems (Chaurey and Kandpal, 2010).

For proper integration of renewable resources, different kinds of optimization methods have been explored as a part of the design process of the decentralized renewable energy system such as linear programming, goal programming, knowledge-based approach, etc. (Hiremath et al., 2007; Iniyan and Sumathy, 2003; Jebaraj and Iniyan, 2006; Ramakumar et al., 1992; Rozakis et al., 1997). In those methods, algorithms are constructed so that the system could be designed to meet the given loads and its configuration would be optimized vis-à-vis various criteria such as the unit cost of energy delivered (Lambert et al., 2005). The common steps for optimization can be described as follows (Kumar et al., 2009):

(i) Availability of local renewable resources is assessed.
(ii) Daily and monthly loads are assessed and forecasted.
(iii) Performance and cost characteristics of each energy conversion device are obtained.
(iv) All the candidate system designs and configurations are identified so that the loads are met under various combinations of available resources and the given conversion devices.
(v) The optimal system design is selected from the candidate designs vis-à-vis a certain criterion such as the unit cost of energy delivered.

Though application of these optimization methods enables a planner to properly design the optimal configuration of decentralized systems, there are still many cases where the design of integrated systems has not been well optimized or only a single renewable resource has been utilized despite the possibility of integrating additional resources for a better service of energy supply. In other words, the step (i) above is not being properly undertaken. If decentralized systems fail to fully

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Table 1
Profile of Kaylapara village (Census 2001).

Number of households	619
Total population	3537
Total area available for cultivation	169 ha
Total area of the village	358 ha

utilize locally available renewable resources, the system operation would become less cost-effective, eventually leading to higher cost of electricity (COE).

Another major challenge in the planning process of a micro-grid system is to estimate accurately the maximum coincident load that the prospective consumers are to impose on the system. The load estimated is an important input for proper sizing of the micro-grid. However, making load projections that reflect reality is still a difficult task to accomplish, especially for prospective consumers who have little exposure and experience with electrification (ESMAP, 2000). Provided that prospective users generally have little knowledge of benefits of electricity, it is difficult to predict the number of household connections in a particular project site under a certain level of service and tariff. Thus, step (ii) above is also difficult to accomplish in a precise manner.

The authors explored the relationship between the household's decision for connection to the micro-grid and their socio-economic characteristics by investigating a sample PV micro-grid project site in India (Kobayakawa and Kandpal, 2014a). It has been found that household's characteristics such as number of school-going children, number of rooms in the house, landholding, income level, and livestock holding show significant difference between households who have connected to the micro-grid and those who have not. The resulting statistical model has been able to predict with high probability whether a particular household with a specific set of socio-economic variables would choose to connect to the micro-grid.

However, those important socio-economic characteristics might differ depending upon the site condition where a micro-grid system is installed such as user's lifestyle, climatic condition, agricultural practice, and so on. Thus, it may be difficult to apply the developed model at completely different sites in order to make accurate predictions as to which households would connect to the micro-grid. Furthermore, once consumers start using electricity, demands tend to grow significantly over time due to consumers' aspirations for additional uses (ADB, 2010; Ulsrud et al., 2011). This gradual demand growth makes it even more difficult to predict future electricity consumptions in an accurate manner.

Under this situation, a thorough ex-ante optimization of the design and configuration of a decentralized system would be quite challenging. Instead, a more realistic approach would be to follow “learning by doing” process and introduce a phased approach in developing such a system (Kobayakawa and Kandpal, 2014a). For example, at the initial phase, the system is designed and constructed within a limited coverage of consumers according to preliminary demand estimation which may lack accuracy. At the second phase, the micro-grid will be extended further and the power plant capacity may be augmented accordingly. More accurate demand estimation will be available for the second phase development if it takes into account the operational data of the initial phase such as household connectivity with particular socio-economic characteristics and monthly electricity consumption per household.

Table 2
Details of the power plant.

Designated peak power of the plant	120 kWp (10 kWp exclusively for water pump)
Module capacity	150 W × 800 (polycrystalline solar cells)
Battery bank	Four sets each of 240 V, 800 Ah
Hours of electricity supply	5–6 h
Length of distribution line	4 km: three phase, 400 V
Number of beneficiaries	approx. 200
Month of commissioning	March 2006

Table 3
Major appliances used by 5-point consumers.

Appliances	Possession %	Others
TV with DVD	83	Average hours of use per household: 1.8
Mobile phone	83	Average number of phones per household: 1.3
Electric fan	17	–

Table 4
Tariff structure for users of Kaylapara PV power plant.

Type of connection	No. of households	Initial payment	Monthly payment
3-point connection	163	Rs. 1000	Rs. 100
5-point connection	33	Rs. 1500	Rs. 150

This phased approach would be effective in order to cope with the growing demand for electricity (Kobayakawa and Kandpal, 2015).

With the above understanding, an attempt is made in this study, first, by using the optimization software HOMER (hybrid optimization model for electric renewable), to review an actual case of the existing decentralized renewable energy system in West Bengal of India for the purpose of finding whether its configuration has been optimized in terms of integration of local resources. The degree of effective utilization of local renewable resources is assessed with particular attention for the review. The project report of the existing system made at the design stage is also reviewed and recommendations are made for future improvement. Second, taking into account that the phased approach for micro-grid development would be effective but its optimization process has not yet been much explored so far, HOMER is used for studying different scenarios of load growths in order to demonstrate the optimization of expansion process. Costs and benefits of various expansion cases have also been analyzed.

Assessment of the existing system

Outline of the system

A 120 Wp PV power plant has been installed in the village, Kaylapara, of Sagar Island in Suderbans area of the state of West Bengal, India. The power plant run by West Bengal Renewable Development Agency (WBREDA) started operation in March 2006 and supplied electricity to 196 households in December 2008. While a majority of the users are households, some small retail shops (but not other commercial consumers)[2] are also connected.

For residential use, electricity is supplied for 5 to 6 h in a day subject to the seasonal change in the availability of daylight. The power supply normally starts around 17:00 in winter and 18:00 in summer. The profile of the village and the specifications of the power plant are presented in Tables 1 and 2, respectively (Chakrabarti and Chakrabarti, 2002; Chaudhuri, 2007; Directorate of Census Operations, 2004; Moharil and Kulkarni, 2009).

At the time of a new connection, each beneficiary household is offered two options: a 3-point connection or a 5-point connection. Three 20-W tube lights are provided for the 3-point connection, and two additional connections are available for the 5-point connection. Additional connection points can be used for any purposes (up to 150 W per household) depending upon the users' needs such as operating a TV, running a fan, or charging mobile phones. Table 3 presents the major appliances being used by households with 5-point connections randomly selected for interviewing. The initial charges as well as the

[2] Consumers who use electricity for commercial activities such as charging batteries, photocopying, grinding, fabrication, computer education are often observed in Sagar Island. But due to the limitation of available power, these commercial uses are restricted in Kaylapara village.

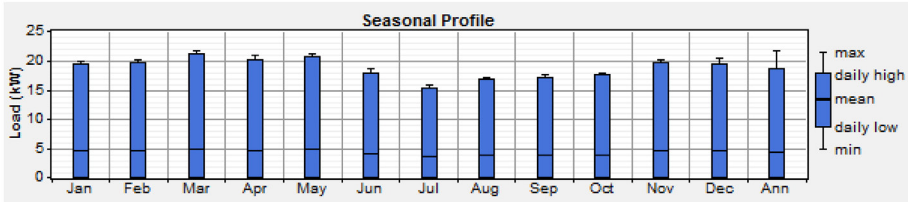

Fig. 1. Monthly load profile.

tariff structure are given in Table 4. If a household fails to pay the tariff for three consecutive months, the service is disconnected.

Optimization by HOMER

The configuration of the PV system in the Kaylapara village is assessed by using the optimization software HOMER in order to find whether it has been optimized in terms of integration of locally available renewable resources. HOMER estimates a system's technical feasibility and then performs the economic analysis and ranks the systems according to total net present cost (NPC) (Asrari et al., 2012; Dekker et al., 2012; Hafez and Bhattacharya, 2012; Lambert et al., 2005; Mondal and Denich, 2010; Ngan and Tan, 2012). In the following sections, the availability of local renewable resources is reassessed with particular attention to biomass resources. Then, HOMER is performed for comparisons and analysis of different configurations of decentralized integrated renewable energy systems to identify a potential alternative with the lowest NPC.

Description of input parameters

HOMER requires some input parameters in order to provide optimization results for different configurations of systems. These input parameters are primary load inputs, renewable resource availability inputs, capacity of power generated, initial costs per unit for each different component. Load profiles are obtained from the actual operational data. As for renewable resource availability, while the existing system only considers solar resource, wind and biomass resources are also considered. All these parameters are further elaborated in the following sub-sections.

Load profile

Figs. 1 and 2 illustrate the monthly and daily load profiles of the existing PV power plant as input for HOMER. The hourly load data of the Kaylapara power plant are available from the months of November 2006 to April 2008. Since the number of connected households varies, the daily load profile during the period is calculated with an assumption that average per-household daily consumption of each month is stable.

Solar radiation

The solar radiation profile of the Kaylapara village (21°45′ North, 88°10′ East) is considered for the analysis undertaken in this work.

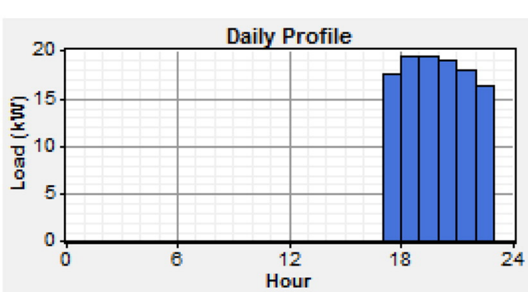

Fig. 2. Daily load profile (January).

Solar radiation data were obtained from the NASA Surface Meteorology and Solar Energy website (NASA). The annual average solar radiation for this region is 4.8 kWh/m^2/day. Fig. 3 shows the solar radiation profile over a one-year period.

Wind speed

The wind speed profile of Fraserganj, about 15 km south of Kaylapara, is available and used in this work since the measurement was done by WBREDA for the purpose of establishing a wind power plant. The annual average wind speed for this area is 4.88 m/s. Fig. 4 shows the wind speed profile over a one-year period.

Biomass

As per the responses received during the interviews of households conducted in the Kaylapara village, woody biomass resources seem to be becoming scarce in the surrounding areas due to their intensive use for cooking purpose. Therefore, it is not realistic to utilize biomass resources as fuel for electricity generation via such technology as biomass gasification-based power plant (BGPP). In this section, the possibilities of introducing fuel-saving devices for cooking, i.e., solar cookers, improved cookstoves, and community biogas plant, are explored and potential availability of resultant excess fuelwood is assessed.

Assumption of the current fuel mix for cooking purpose. In Sagar Island, fuelwood is the major source of energy for cooking as is the case with the most of rural India, but cattle dung also plays an important role in fulfilling villagers' cooking energy requirements. Crop residues such as

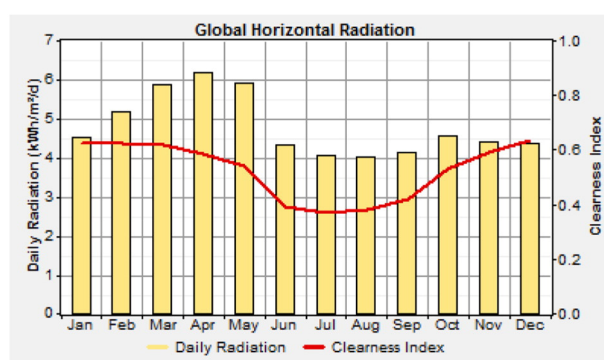

Fig. 3. Solar radiation profile.

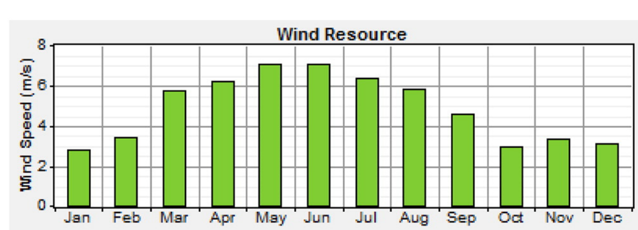

Fig. 4. Wind speed profile.

Table 5
Estimated equivalent number of meals cooked by different fuel types.

Fuel type	Amount used for cooking (kg/day)	Equivalent number of meals cooked
Cattle dung (dry)	0.38	0.94
Fuelwood	0.49	1.36[a]
Crop residue	0.05	0.20
Total	–	2.50

[a] Per capita fuel requirement for cooking in case of fuelwood is assumed to be 361 (g/meal) (Ravindranath, 1997).

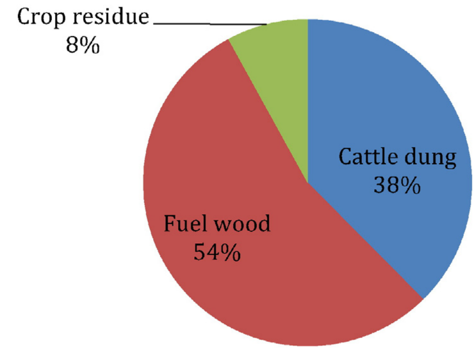

Fig. 5. Fuel mix for cooking (% equivalent number of meals cooked).

straw are also used for cooking but a larger portion of the residues are used as fodder for cattle. Kerosene and LPG are not used as fuel for cooking purpose due to their high costs.

The current consumption of cattle dung can be estimated from the average number of cattle raised by the village households. As the number of cattle per household is found to be 2.14 from the interviews, the total cattle in the village is assumed to be 1324 (= 2.14 × 619). Taking the following assumptions, the total of 1324 kg of dry dung would be available for daily cooking. Since the mean number of family members per household is 5.6, approximately 0.38 kg of dry dung would be available for cooking per capita per day.

- 10 kg of fresh dung is produced by a cattle head per day.
- Fresh dung contains 80% moisture.
- Half of the total cattle dung is used for cooking.[3]

Provided that per capita fuel requirement for cooking in case of cattle dung is assumed to be 404 (g/meal), 0.94 meals can be cooked from the available dry dung daily (Ravindranath, 1997). As it is found from the interviews that the villagers have 2.5 meals per day on average, the remaining 1.56 meals (= 2.5–0.94) need to be cooked by fuelwood and crop residues.

Another literature indicates that the monthly consumption of fuelwood and crop residues for cooking is around 90 kg per household in West Bengal (GIZ, 2014). Thus, per capita daily consumption of fuelwood and crop residues for cooking can be calculated as 0.54 kg, which is equivalent for cooking 1.48 meals. This result is found to be consistent with the above estimation (1.56 meals).

Then, estimation is made for consumption of crop residues as cooking fuel. In this area, the major crop residues which can be used for cooking are considered to be straw and rice husk. The following figures have been obtained for this purpose (Debnath, 2013):

- Rice production in Sundarbans: 320–400 kg per bigha (2370–2960 kg/ha)
- Areas for paddy cultivation in Kaylapara village: 135 ha (80% of the total cultivated land)
- Crop residue to production ratio: 1.8 (rice)

The total paddy production is calculated to be around 360 tons, and therefore, 648 tons of residues (straw and husk) are found to be available. Assuming that approximately 10% of the total residues are used for cooking fuel, 0.05 kg of crop residues is available per capita per day.[4] Thus, out of the total sum of 0.54 kg, 0.49 kg of fuelwood and 0.05 kg of crop residue is used for cooking.

The resulting summary of fuel mix for cooking is shown in Table 5 and Fig. 5.

Introduction of fuel-saving devices. In order to save the fuelwood consumption for domestic cooking, it is proposed to introduce and promote the use of fuel-saving devices such as solar cookers, improved cookstoves, and community biogas plant. Rates of dissemination are assumed for each of the devices.

Solar cooker. Suppose 10% of the total village households (62 households) start using a solar cooker in place of the current fuel mix for cooking one of the meals, approximately 0.069 ton/day (= 0.20 kg × 62 × 5.6)[5] of woody biomass would be available daily for use as feedstock in BGPP.

Improved cookstove. Similarly, if we suppose that 50% of the total village households (310 households) start using improved biomass cookstoves in place of the traditional cookstoves currently in use, the same amount of 0.17 ton/day (= 0.49 kg × 0.2 × 310 × 5.6)[6] woody biomass would be available daily for running BGPP.

Community biogas plant. Another option to save fuel consumption for cooking is the introduction of community biogas plants. Considering the standard value of gas production yield from raw dung is 0.037 m^3/kg (Imam et al., 2013), per capita gas production from the available cattle dung is calculated as 0.11 m^3 (= 0.38 cattle × 10 kg × 0.8 (collection rate[7]) × 0.037 m^3/kg). Since the biogas plant would require 0.07 m^3 of gas per meal (Ravindranath, 1997), the available dung in the village can produce biogas sufficient to cook 1.6 meals per capita per day. In other words, consumption of fuelwood for cooking 0.58 meals, i.e., 0.21 kg, can be saved, leading to a total saving of 0.74 ton/day (= 0.21 kg × 3537) in the whole village. Thus, the introduction of community biogas plants would save 0.74 tons of woody biomass daily for running BGPP.

Fuelwood savings from different combinations of fuel-saving devices are calculated and summarized in Table 6. It is found that the potentially available excess fuelwood varies from 0.069 to 0.91 tons/day according to the degree of success in disseminating different kinds of fuel-saving devices. However, taking into account the increasing scarcity of woody biomass in the region, it is appropriate to consider only 60% of the excess fuelwood under the most conservative scenario, i.e., 0.041 tons/day, as fuel input for BGPP for the subsequent analysis.

Furthermore, in order to take into account the uncertainty in estimating the amount of biomass saved, a sensitivity analysis will be conducted in the subsequent section of "Sensitivity analysis" over varied amounts of available biomass resources according to different rates of dissemination and combinations of these technologies.

Cost implications of introducing fuel-saving devices. As government subsidy schemes are available for each of the proposed alternative technologies for domestic cooking as shown in Table 7 (MNRE, 2013; TERI, 2004), their disseminations would require public expenditure for the subsidies. For the scenario of having 0.041 tons/day of woody biomass resource,

[3] Normally, 40–70% of all manure produced by Indian cattle is used as fuel for cooking; the rest is returned to the fields as fertilizer.

[4] The total population of the village is 3537 according to Census 2001.

[5] The number of the connected households is about 200 and the mean number of family member per household is 5.6.

[6] Field studies have shown that use of efficient stoves results in about 20% saving of fuelwood compared with traditional stoves. (Ravindranath et al., 2005)

[7] It is assumed that as much as 80% of the total cattle dung will be used as input to the biogas plant. It is not necessary to keep a part of dung for fertilizer since slurry can be used for that purpose.

Table 6
Fuelwood savings from introducing different combinations of fuel-saving devices.

	Traditional cookstove			Improved cookstove			Solar cooker	Community biogas	Total saving of fuelwood (ton/day)
	Fuelwood	Crop residue	Dung cake	Fuelwood	Crop residue	Dung cake			
Base case	×	×	×						
Scenario I	×	×	×				×		0.069
Scenario II	×	×						×	0.74
Scenario III	×	×					×	×	0.84
Scenario IV				×	×	×			0.18
Scenario V				×	×	×	×		0.23
Scenario VI				×	×			×	0.83
Scenario VII				×	×		×	×	0.91

public expenditure of USD513 (= INR23,100 = INR1155 × 20),[8] USD72 (= INR3250 = INR65 × 50), and USD12,800 (= INR575,000) are necessary for subsidizing dissemination of solar cookers, improved cookstoves, and community biogas plants, respectively. In case of introducing BGPP as a generation component, these expenditures also need to be considered to secure necessary fuel inputs. However, they are relatively small and thus shall not have significant impacts on the subsequent optimization results. Installation of community biogas plants may require relatively significant costs, but their benefits would not be limited to fuel savings but include cleaner in-house environment, improved health condition, saving of cooking time, etc. (Government of India, 2002).

System description and specification

The integrated renewable energy system under consideration consists of five main components which include PV array, wind turbine, BGPP, batteries and power conditioning units (converters) as shown in Fig. 6. The descriptions and the design specifications of the selected components are provided in the following section. Input data for the HOMER software are summarized in Tables 8 and 9. The HOMER software simulates the system costs based on the US dollar. The cost data of PV array, batteries and converter are based on the actual costs incurred for installing the existing system. The costs of wind turbine and BGPP are obtained from the literature (Ngan and Tan, 2012; Nouni et al., 2007). As replacements of PV array, wind turbine and BGPP do not accompany civil works, their replacement costs are less than the capital costs by the amounts corresponding to their civil works. The O&M cost is also based on the actual cost incurred for the existing system.

PV modules

As indicated above, the actual PV array size of the installed system is 120 kWp, out of which 10 kWp is exclusively used for water pumps installed within the premise of the power plant during the daytime. Hence, for the subsequent analysis, the system capacity connected to the load via the micro-grid is taken as 110 kWp. Since the integration of the other renewable sources is considered in this study, the size of the PV plant varied from 10 kWp to 110 kWp with an interval of 10 kW.

Wind energy conversion system

The wind turbine included in the present analysis is BWC Excel-S model with a rated capacity of 10 kW. To allow the simulation program to find an optimum solution, four options are fed into the software for analysis: 0 (no turbines), 1 turbine, 2 turbines or 3 turbines.

Biomass gasification-based power plant (BGPP)

BGPP consists of biomass preparation unit, biomass gasifier, gas cooling and cleaning system, internal combustion engine and electric generator (Mukhopadhyay, 2004; Nouni et al., 2007). Options are given in terms of the capacity of the system, namely, 0, 10, 20, 30 or 40 kW.

[8] 1USD = 45INR (as of Jan. 2011).

Since the fuel availability depends on the hypothetical degree of success in dissemination of solar cookers or improved cookstoves, sensitivity analysis is conducted over the parameter.

Battery

For the purpose of energy storage, lead acid batteries are included in this analysis for economic considerations. In this case, commercially available battery models, such as Hoppecke 8 OPzS, are used in the scheme. To find an optimum configuration, the battery bank is assumed to contain any number of (0, 120, 240, 360 or 480) batteries.

Power converter

A power converter is used to maintain the flow of energy between the AC and DC components. The capacity is varied from 10 kW to 60 kW with an interval of 10 kW.

Results and discussion

Based on optimization results performed by HOMER for the defined parameters all feasible systems are categorized by their types. The most economic system in each category is then chosen as the representative

Table 7
Government subsidy schemes for solar cooker and improved cookstove.

Energy saving device	Cost range (INR)	Government subsidy (INR)	Ave. subsidy (INR)
Box type solar cooker	3500–4200	30% of the product cost (maximum)	1155
Improved cookstove	150–180	60–70 (approx. 40% of the product cost)	65
Community biogas plant[a]	550,000–600,000	Case by case (assume 100% in this case)	575,000

[a] Construction cost for community biogas plant with capacity of 85 m^3 × 2 (Government of India, 2002).

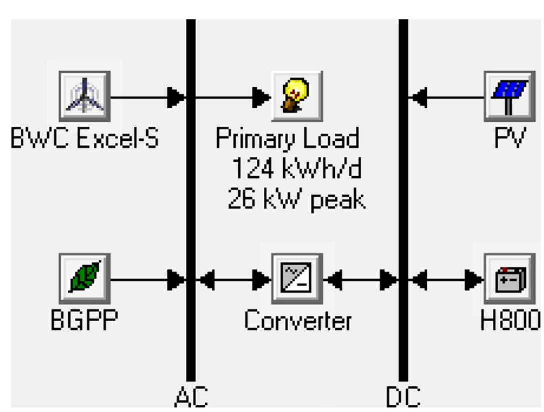

Fig. 6. Configuration of the renewable energy system as designed in HOMER.

Table 8
Input data on costs of different technology options.

Options	Capital cost (USD)	Replacement cost (USD)	O&M[a] cost (USD)
PV	\$4.64/W	\$3.89/W	\$79/kW/year
Wind (10 kW)	\$30,730/turbine	\$22,900/turbine	\$992/year
BGPP	\$909/kW–\$1270/kW	\$749/kW–\$1045/kW	\$0.2/h–\$0.6/h
Battery	\$148/battery	\$148/battery	\$2.5/battery/year
Converter	\$1250/kW	\$1250/kW	\$214/kW/year

[a] Operation and maintenance.

Table 9
Input data on sizes and other parameters of different technology options.

Options	Options on size and unit numbers	Life	Other information
PV (kW)	0, 10, 20, …, 110	30 years	Derating factor = 80%
Wind (turbines)	0, 1, 2, 3	15 years	Weibull k = 2.0
BGPP (kW)	0, 10, 20, 30, 40	15,000 h	Minimum load ratio = 30%
Battery (number)	0, 120, 240, 360, 480	2742 kWh	Nominal capacity 800 Ah
Converter (kW)	0, 10, 20, 30, 40, 50, 60	15 years	Efficiency = 90%

of that category. Finally, the selected representative systems from all categories are ranked in order from the most to the least economic. The annual real interest rate is taken as 4% for economic analysis.[9] A summary of the results of this procedure can be found in Table 10.

Category 1: PV–biomass(BGPP)–battery

As shown in Table 10, a PV–biomass–battery system, which consists of 30 kW PV array, 20 kW BGPP, 120 batteries, and 30 kW power converter, would be the most economically feasible with a minimum total NPC of \$331,856 and COE of \$0.511/kWh. Compared with the actual PV–battery system, the total NPC is lower by \$741,683. Fig. 7 depicts the share of PV and BGPP in producing the demand electricity of the Kaylapara village in different months of the year. As can be observed, the share of BGPP is more considerable during the monsoon season when the availability of solar radiation is limited. The fuel-saving devices may need to be introduced for ensuring the biomass input of 0.041 tons/day for BGPP. However, even if their introduction costs (Table 7) are considered, this category provides the lowest cost option.

Category 2: PV–wind–biomass(BGPP)–battery

As Table 10 reveals, the second economically viable system is the PV–wind–biomass–battery design, which consists of 30 kW PV array, one 10 kW BWC Excel-S wind turbine, 20 kW BGPP, 120 batteries and 30 kW power converter, with a total NPC of \$387,210 and a COE of \$0.596/kWh. The wind potential is added to Category 1, but it is less economical than biomass resource. Compared with the actual system, the total NPC is lower by \$686,329. Fig. 8 reveals the share of PV, a wind turbine and BGPP in producing the demand electricity in different months. Compared with Category 1, electricity production from PV plant is lesser. Instead, the wind turbine and BGPP produce more electricity especially during the months when wind resources are relatively abundant and solar radiation is lower due to the monsoons. This category of integration would remain as the second lowest cost option even if the introduction costs of the fuel-saving devices are taken into consideration.

Category 3: PV–wind–battery

The third economical category is the PV–wind–battery system, which consists of the 30 kW PV array, one 10 kW BWC Excel-S wind turbine, 480 batteries and 30 kW power converter, with a total NPC of \$429,305 and a COE of \$0.660/kWh. The total NPC is lower by \$644,234 than that of the actual system. Fig. 9 shows the monthly share of PV and wind turbines in producing the demanded electricity. A significant share of wind turbines in supplying electricity can be observed during the months from March to August when wind speeds are relatively high.

Category 4: PV–battery

The least economically feasible option is that of the PV–battery system, which is the same category with the existing system. Since the required PV array capacity turns out to be almost one-third of the actual system, a total NPC and COE is lower by \$642,784 and \$0.99/kWh, respectively. However, although the current PV array capacity is sufficient, it is not possible to further increase the number of consumers due to the limitation of the battery size. If more batteries are added, it would be possible to supply electricity to more consumers. Alternatively, even without adding batteries, it would be possible to supply excess electricity for day-time use such as water pumping for irrigation purposes.

Sensitivity analysis

Sensitivity analysis is conducted over different values of available biomass resource amounts as shown in Fig. 10. It is found that PV–biomass–battery system is the optimum configuration in most cases irrespective of biomass availability. Generally speaking, contribution of BGPP required for power generation becomes higher and that of PV becomes lower as biomass resource availability increases. This is because BGPP is the most cost-effective component while PV is the least cost-effective. The cost-effectiveness of wind turbine is in-between the two components and the PV–wind–biomass–battery system occasionally becomes the most feasible configuration depending upon biomass resource availability and other factors. Therefore, as expected, the degree of success in dissemination of the fuel-saving devices would be a key factor in determining the system configuration as well as the life-time cost of the system.

Review of the detailed project report (DPR)

As indicated above, the actual system configuration has some deviations from the simulation results using HOMER. In order to identify the ground for the original design, the DPR obtained from WBREDA has been reviewed. Some findings are as follows:

First, in the DPR, only the option of PV–battery was considered and possibilities of integrating other renewable resources were not explored. If the introduction of fuel-saving devices such as solar cooker, improved cookstoves or community biogas plants were considered as a part of the project component, and the possibility of using excess fuelwood for BGPP was sought, the hybrid PV–biomass–battery system might have been a strong candidate with the highest feasibility. Even if the introduction of these devices might not be successful, hybrid PV–wind–battery system could have reduced the NPC compared with the original PV–battery system.

Second, the optimization process for determining the system size and configuration was not clearly stated in the DPR. The requirement for the system should have been given in the form of project output, i.e., the number of village households to be electrified, rather than in the form of technical specification, i.e., 120 kWp PV power plant, so as to provide the contractor with flexibility in seeking optimality and integration of various resources in the design process.

Third, as shown in Table 11, the demand forecast in the DPR lacked accuracy not only in the number of connections but also in the per-consumer consumption. Since electricity demand is significantly affected by design parameters such as micro-grid coverage and tariff structure, these parameters should have been clearly set in the DPR with proper grounds. Yet, as stated in the beginning, accurate demand estimation is often quite challenging. In such a case, the phased

[9] The average real interest rate in India during 2003–2012.

Table 10
Results of HOMER optimization.

	PV (kW)	Wind (kW)	Biomass (kW)	Battery (number)	Conv. (kW)	Capital cost ($)	O&M cost ($/year)	Total NPC ($)	COE[a] ($/kWh)	BGPP (h)
Actual	110	0	0	480	120	$753,900	$18,485	$1,073,539	$1.651	–
Category 1	30	0	20	120	30	$221,168	$6401	$331,856	$0.511	367
Category 2	30	10	20	120	30	$251,898	$7825	$387,210	$0.596	192
Category 3	30	10	0	480	30	$284,473	$8376	$429,305	$0.660	–
Category 4	40	0	0	480	30	$302,116	$7439	$430,755	$0.663	–

[a] Cost of electricity.

approach can be considered. Simulations are undertaken in the following section in order to find how adjustment of the system design during expansion process can improve its optimality and thus financial viability.

Simulation of the system expansion

Successful decentralized rural electrification projects often face with significant increase of electricity demands from the consumers. In the case of the Kaylapara project, a strong need for the grid extension to potential users outside of the original grid coverage has been perceived (Kobayakawa and Kandpal, 2014a). In order to cope with such a demand growth, it has been pointed out that it would be effective to augment the system capacity by taking advantage of modular characteristics of renewable system (Jebaraj and Iniyan, 2006). In this section, the optimization of the system expansion in the Kaylapara village is simulated by using HOMER under different expansion cases as summarized in Table 12. Pros and cons of each expansion case are also discussed in terms of its contribution to community welfare and financial viability of the project.

Expansion cases under consideration

Case 1: extension of the grid coverage to the potential consumers

In Case 1, the grid is extended farther so that an additional 200 consumers could make new connections under the current two payment options (monthly payment of Rs.100 for 3-point and Rs.150 for 5-point connection). As the total number of connections is expected to double, electricity demand will also double with an assumption that demand density of medium and high income consumers is identical to the original service area. Additional construction costs will be incurred for augmentation of the plant capacity as well as for the extension of the micro-grid. In addition, tariff revenue will increase from new consumers. The daily load profile in this case is shown in Fig. 11.

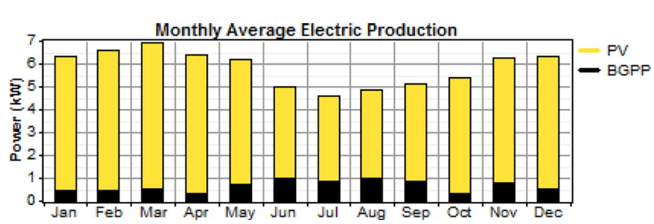

Fig. 7. Share of PV and BGPP in electric production.

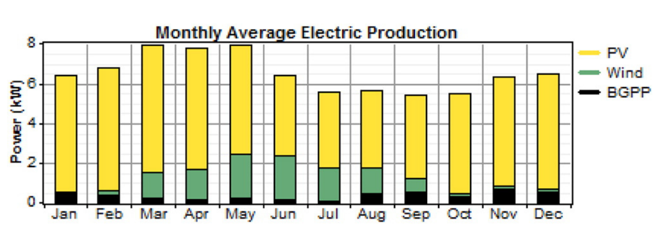

Fig. 8. Share of PV, wind and BGPP in electric production.

Case 2: addition of a connection option to the lower income group

In Case 2, the new service area covered by the grid extension is limited to half of Case 1 and around 100 new consumers will be added under the current two payment options. Besides, a new payment option (monthly payment of Rs.60 for 2-point connection) is introduced, which enables another 100 consumers from lower income groups to connect to the grid. Those who cannot afford the current payment option but live within the current reach of the grid are encouraged to join beneficiaries of the project, and therefore, no extensions of the grid lines are envisaged for these new connections (Kobayakawa and Kandpal, 2014b). The daily load profile in this case is shown in Fig. 12.

Case 3: addition of a connection option for productive use

Currently, electricity use is only allowed for lighting (3-point) and small appliances such as TV, fans, and mobile phones (5-point). If a new payment option allows consumers for any productive use, it would contribute to enhance income-generating activities and create new jobs in the village. In Sagar Island, many villagers own fish ponds to retain rain water and some of them pump up the water for irrigation purpose during the dry season. The interview result shows that around 28% of the villagers use irrigation pumps with monthly expenditure of Rs.166 on average to purchase kerosene as a fuel. In Case 3, a new payment option is created to allow a consumer to use sufficient electricity for running an irrigation pump. If the monthly tariff for the new option is set at Rs.150, it would successfully encourage the farmers to switch over to electricity to run their irrigation pumps. Thus, the power plant capacity needs to be augmented according to the increased level of demand, and revenue will increase due to the higher payment option. It is assumed that 55 of the farmers newly obtained connections for using

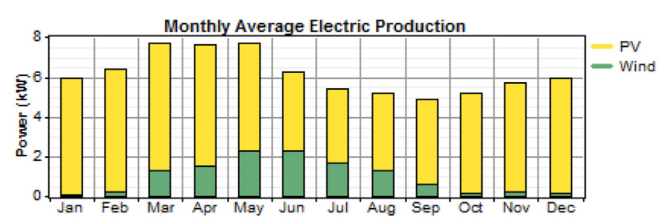

Fig. 9. Share of PV and wind in electric production.

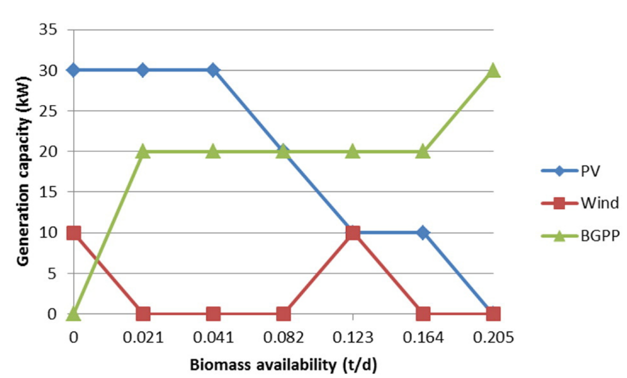

Fig. 10. Biomass availability vs. generation capacity of each component.

Table 11
Comparison of predicted and actual electricity demands.

	Load type	Number of connections	Per-consumer consumption (W)	Peak load (kW)	Annual consumption (kWh/year)
DPR	(1) Domestic			70	100,000
(expected)	(a) Low income	750	42		
	(b) Medium income	500	100		
	(c) High income	10	500		
	(2) Shops	100	250		
Actual	(1) Domestic		95	22	37,595
(Dec 2008)	(a) Medium income	163			
	(b) High income	33	(on average)		

Table 12
Input parameters.

	Load type	Monthly tariff (Rs/mo)	Total length of the grid (km)	Number of connections	Connected load (kWh/d)
Original	Total		4.1	196	103
(110 kWp PV)	Medium income group	100		(163)	
	High income group	150		(33)	
Case 1	Total		8.2	400	210
	Medium income group	100		(330)	
	High income group	150		(70)	
Case 2	Total		6.2	400	182
	Low income group	60		(100)	
	Medium income group	100		(250)	
	High income group	150		(50)	
Case 3	Total		4.1	251	124
	Medium income group	100		(163)	
	High income group	150		(33)	
	Irrigation pumps	150		(55)	

electricity pump of 1.5 HP for two hours daily (9:00–11:00) during the dry season. The daily load profile in this case is shown in Fig. 13.

Results and discussion

Optimizations are conducted for each of the three expansion cases by using HOMER. It is assumed that the expansions are undertaken after the first 15 years out of the total 30 years of the project life. By taking a chance at expansion, the major components such as a converter and batteries are also replaced considering their lives. The system expansion from the original design of 110 kWp PV–battery system is simulated vis-à-vis each of the increased demand levels described in the previous section. The components under consideration for expansion are PV, wind turbine, BGPP, batteries and converters (Table 13). Design specifications and cost information of each component are the same as indicated in Section "System description and specification". The biomass availability is assumed to be 0.041 t/day in each of the cases.

The results of the simulation are shown in Table 14. O&M cost includes costs for replacement of components as well as fuel purchase for BGPP. It is widely recognized that long-term sustainability and effectiveness of rural electrification programs appear to critically depend on the degree of cost recovery. From this financial perspective, charging tariffs that at least cover O&M costs is essential (Gavalda et al., 2004; Kirubi et al., 2008). In view of this aspect, the ratio of "revenue/O&M cost" is calculated in order to indicate to what extent tariff revenue can cover the expenditure for O&M.

In Case 1 and Case 2, generation capacity is increased by adding BGPP component. In Case 3, additional generation capacity is not required as the original PV module had sufficient capacity. Since the original size of the converter was found to be too large compared with the demand level, it was replaced with a smaller size converter at the

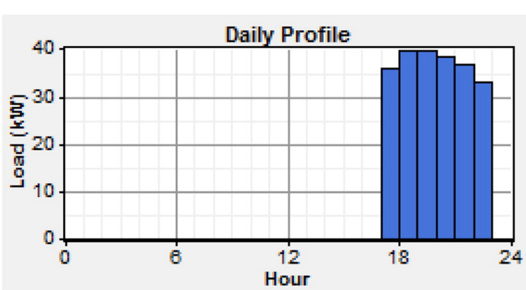

Fig. 11. Daily load profile (January).

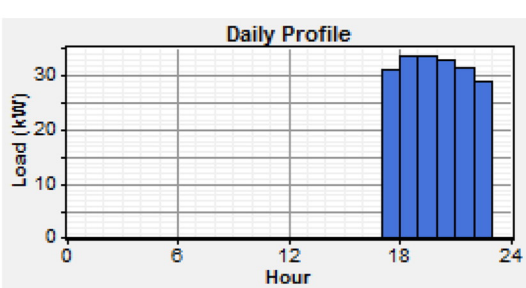

Fig. 12. Daily load profile (January).

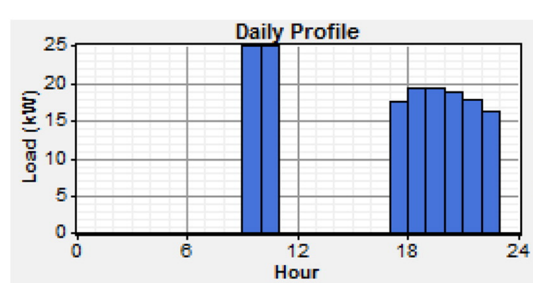

Fig. 13. Daily load profile (January).

Table 13
Input data on parameters of expansion components.

Options		Options on size and unit numbers	Life (year)	Other information
Original configuration	PV (kW)	110	15 years[a]	Upfront cost = 0
	Battery (number)	480	2742 kWh	Upfront cost = 0
	Converter (kW)	120	15 years	Upfront cost = 0
Additional configuration	PV (kW)	0, 10, 20	30	Derating factor = 80%
	Wind (turbines)	0, 1, 2, 3	15	Weibull $k = 2.0$
	BGPP (kW)	0, 10, 20, 30, 40, 50	15,000 h	Minimum load ratio = 30%
	Battery (number)	0, 120, 240, 360, 480	2742 kWh	Nominal capacity 800 Ah
	Converter (kW)	0, 10, 20, 30, 40, 50, 60	15	Efficiency = 90%

[a] The remaining life is 15 years since the expansion is undertaken 15 years after the initial installation.

time of expansion, resulting in the reduction of O&M costs of the system. Hence, all three expansion cases required additional capital investments, but less yearly O&M costs. Further, tariff revenue increases for all the cases due to additional connections, and consequently "revenue/O&M cost" ratio improves significantly, which would enhance the financial viability of the system. Cost of electricity (COE) improves for all the cases due to increased power generation. Especially in this case, the COE of the original system is very high due to the oversize of the PV modules and the converter, having a significant room for improvement.

Comparing among the three cases, Case 1 shows the highest "revenue/O&M cost" ratio and the lowest COE. Although Case 1 expansion requires the largest amount of investments among the three cases, the increase of tariff revenue would be also the largest due to the fact that new consumers in the medium and high income groups can afford to relatively higher tariff levels. Thus, the best expansion scenario is Case 1 in terms of efficiency; however, the poorer segment of the community may not benefit from the project as lower tariff option is not available.

Case 2 shows the second highest "revenue/O&M cost" ratio and the second lowest COE after Case 1. Since Case 2 offers a payment option for the lower income group, it has an advantage from the standpoint of social equity but "revenue/O&M cost" ratio becomes less than Case 1. Case 2 expansion may lead to higher administrative costs as additional payment options can increase complexity in tariff collection and accounting procedures.

Case 3 requires the least capital investment as the additional demand occurs only during daytime allowing the current size of PV module and less size of converter. The advantage of Case 3 expansion is that it can improve financial viability without making significant additional investments except major replacement costs. On the other hand, this expansion case has a drawback in which the benefits of the project may be limited to the relatively rich households in the community that can afford additional payments for running electric irrigation pumps.

The simulation result may be different depending upon conditions such as additional demand levels and tariff settings. However, it can be concluded that system expansion, if properly done, offers an opportunity not only to improve COE but also to enhance tariff revenue. COE can be reduced through an accurate re-assessment of the load and re-sizing of system components. Tariff revenue can be increased as more demands are accommodated and more consumers are connected to the grid. In sum, the phased approach for development of an off-grid micro-grid system is found to be effective for enhancing community welfare as well as financial viability of the project.

Conclusions

This study indicates that using the existing system design and electricity demanded, proper optimization is imperative in designing a decentralized renewable energy system for maximizing its cost-effectiveness. To this end, emphasis would need to be placed on the following aspects of the design process: (i) effective integration of locally available resources, (ii) output based contract which allows a contractor for flexibility in seeking optimality and resource integration and (iii) accurate prediction of the loads.

For purpose of fulfilling (i), the most challenging part is to assess availability of biomass resources. Since biomass resources are already used intensively for cooking fuel in rural areas where the depletion of forests has become a serious problem, their further utilization for electricity generation requires a careful consideration. However, as BGPP is often a prospective option for decentralized energy systems in terms of cost-effectiveness, it is worth exploring the possibility of introducing fuel-saving devices and utilizing the excess fuelwood.

Besides, ensuring (iii) above is also challenging as many projects in the past were faced with significant load growths that were unpredictable in the beginning. In such a case, the phased approach in developing a decentralized energy system must be effective, in which not only refurbishment but also expansion of the system vis-à-vis growth of the

Table 14
Optimization results of system expansion.

	System configuration	Initial capital before expansion ($)	Additional capital for expansion ($)	O&M cost ($/year)	Tariff revenue ($/year)	Revenue/O&M cost ratio	COE[a] ($/kWh)
Original	PV 110 kWp Battery 480 Conv. 120 kW	Plant: 753,900 Grid: 21,400 Total: 775,300	–	18,485	5670	0.31	1.65
Case 1	PV 110 kWp BGPP 30 kW Battery 240 Conv. 50 kW	–	Plant: 126,795 Grid[b]: 21,400 Total: 148,195	11,745	11,600	0.99	0.78
Case 2	PV 110 kWp BGPP 30 kW Battery 240 Conv. 40 kW	–	Plant: 114,220 Grid: 10,700 Total: 124,920	10,860	10,270	0.95	0.89
Case 3	PV 110 kWp Battery 240 Conv. 30 kW	–	Plant: 73,175 Grid: 0 Total: 73,175	10,023	7870	0.79	1.26

[a] Cost of electricity.
[b] The unit cost for grid construction is approximately 5200 ($/km) according to the actual case.

load is a scope of the second and subsequent phases. Accurate load prediction would be far easier for the expansion phase as plenty of information is available from the existing consumers.

As the above simulation revealed, system expansion process may provide an opportunity for lowering O&M cost and COE as well as for enhancing financial viability of the project. The former benefit would come from replacement of oversized components and the latter would be realized by increased tariff revenue and reduced O&M cost. Scenarios of system expansion may vary depending upon potential target consumers, but it is important to carefully identify the needs of the community not only in terms of cost-effectiveness but also social equity.

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