Energy for Sustainable Development 34 (2016) 20–29

Contents lists available at ScienceDirect

Energy for Sustainable Development

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

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ARTICLE INFO

Article history:
Received 31 December 2014
Accepted 29 June 2016
Available online xxxx

Keywords:
Micro-grid
Integrated renewable energy system
Optimization
HOMER
Demand growth
System expansion

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.

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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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[1] The views and opinions expressed herein are those of the authors and do not necessarily represent the official views of the Japan International Cooperation Agency (JICA).

http://dx.doi.org/10.1016/j.esd.2016.06.006
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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. This phased approach would be effective in order to cope with the growing demand for electricity (Kobayakawa and Kandpal, 2015).

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

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

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[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.

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