Energy for Sustainable Development 23 (2014) 92–98

Contents lists available at ScienceDirect

Energy for Sustainable Development

A techno-economic optimization of decentralized renewable energy systems: Trade-off between financial viability and affordability—A case study of rural India ☆

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ARTICLE INFO

Article history:
Received 22 March 2014
Revised 19 July 2014
Accepted 28 July 2014
Available online xxxx

Keywords:
Decentralized renewable energy system
Affordable tariff setting
Financial viability

ABSTRACT

Ensuring financial viability for a decentralized renewable energy project and still setting tariffs within the affordability of the users in remote areas with low income is a major challenge. Many decentralized rural electrification projects suffer from financial shortage during operation partly due to lack of tariff revenue. However, if tariff is set beyond reasonable level, it would limit the number of beneficiaries of the project. This study proposes, by taking tariff level as a parameter, a design method that seeks balance between financial viability and affordability. Through the proposed method, relationship among design parameters such as tariff, number of consumers, system cost, revenue projection, degree of cost recovery, and required government subsidy, are identified in a quantitative manner. The design method is further demonstrated by its application to a sample project site in India. As a result, the optimal tariff level is identified in terms of the degree of cost recovery. However, taking into consideration affordability, another option of lower tariff is also possible as far as government subsidy is available to cover shortfalls. Policy makers need to decide tariff setting which would resolve the trade-off to the extent possible by taking into account availability of government subsidy.

Introduction

Decentralized renewable energy systems have been promoted for 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 (Chaurey and Kandpal, 2010). The micro-grid systems also offer the possibility of integrating various locally available renewable resources to establish relatively larger generation capacity systems (Chaurey and Kandpal, 2010).

One of the major challenges of the planning and operational process of the micro-grid system is to decide the trade-off between financial viability and affordability in tariff setting for the electricity being supplied (Ulsrud et al., 2011). It is widely recognized that long-term sustainability and effectiveness of rural electrification programs critically depend on the degree of cost recovery. Generally in successful electricity industry, the total costs of service are covered by the tariffs paid by the consumers (Munasinghe and Warford, 1982). But in case of rural electrification, it is argued that a full cost recovery is not realistic as most of consumers have only limited payment capabilities. It is often required that the tariff cover at least the operation and maintenance (O&M) costs while the capital cost may be covered entirely by subsidies (Gavalda et al., 2004; Kirubi et al., 2008).

However, the requirement to cover all of the O&M costs sometimes end up in a criticism that benefits of electrification are biased toward relatively rich households in the rural community (Khandker et al., 2012). Considering that access to electricity is crucial to human development, tariff needs to be set at well affordable level even for the poor in order to achieve universal access to electricity (World Bank, 2008a). In this context, tariff settings need to be based upon willingness-to-pay (WTP) of potential consumers including the poor (Cust et al., 2007). As such, tariff setting in case of rural electrification requires a difficult task of balancing financial viability and affordability taking into account not only O&M costs of the system but also WTP of the poor segments of the community (Martinot and Reiche, 2000; Ulsrud et al., 2011).

Further, as there is a possibility that price elasticity of electricity emand is high in case of rural electrification (Wison et al., 2010), even small difference of tariff can lead to significant change of electricity demand, and thus significant change of system capacity. In case of off-grid rural electrification where electricity demands need to be

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http://dx.doi.org/10.1016/j.esd.2014.07.007

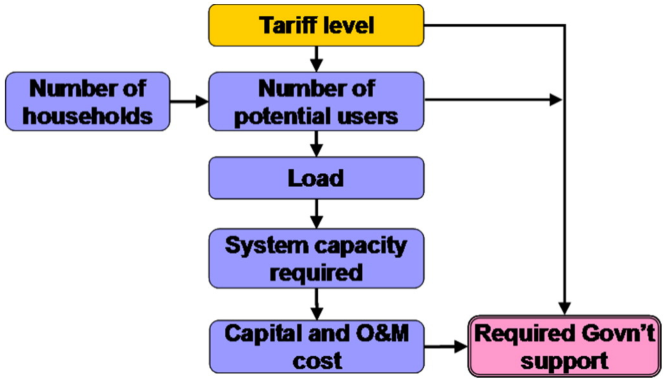

Fig. 1. Flow diagram of the proposed design method.

accommodated by a locally installed system, tariff setting can be quite an important design parameter to define system capacity. Though there have been plenty of studies which deal with optimization procedure of decentralized renewable energy systems, most of them have not focused on tariff setting as a design parameter of the systems (Bajpai and Dash, 2012; Erdinc and Uzunoglu, 2012).

This study explores a design method of a decentralized renewable energy system which seeks the balance between financial viability and affordability in the tariff level. Actual operational data such as electricity load and renewable resource availability are obtained from the actual PV micro-grid system installed in a remote village of Sagar Island in Sunderbans area of the state of West Bengal in India. Willingness-to-pay (WTP) for electricity is derived from a sample village interview and is used for assuming the number of beneficiaries under a certain level of tariff. A different tariff leads to a different number of beneficiaries, and thus a different level of load requirement. Then the system design can be optimized under a certain load requirement by using the optimization software HOMER (Hybrid Optimization Model for Electric Renewables) developed by the US National Renewable Energy Laboratory (NREL). Since the optimization result includes O&M cost of the system, the degree of financial viability can be assessed by comparing expected tariff revenue and O&M cost. The resultant design method proposed in this study will be applicable to any rural electrification projects based on micro-grids.

Theoretical modeling

First, the correlation between the tariff levels and the number of beneficiaries is analyzed assuming monthly flat tariffs. If the tariff level is lower, more households would choose to connect to the micro-grid, leading to a larger demand level (Khandker et al., 2012; World Bank, 2010). Once a certain tariff level is set and the corresponding demand level is known, the system configuration is optimized vis-à-vis the least cost criterion by using an optimization software such as HOMER. The HOMER simulation determines the optimal system configuration by using the net present cost (NPC) of the project over its entire lifespan of operation. NPC includes expenses such as components, component replacements, O&M costs, and initial setup costs. The NPC is calculated within HOMER using Eq. (1) below:

$$NPC = \frac{TAC}{CRF} \tag{1}$$

where TAC is the total annualized cost (which is the sum of all annualized costs of each system component). The capital recovery factor (CRF) is given by Eq. (2) below:

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{2}$$

where N is the number of years and 'i' is the annual real interest rate (%).

Since the simulation results come along with O&M cost required for system operation, the degree of cost recovery can be assessed from calculation of expected revenue from the beneficiaries. Likewise, the system optimization is undertaken for a certain range of tariff levels by following the flow chart shown in Fig. 1.

If the tariff level is sufficiently low for the poor, the number of consumers as well as their total electricity demands will be large, which leads to a requirement for larger capacity of the system, and therefore higher capital and O&M cost of the system. The question is whether or not the expected tariff revenue can cover the monthly O&M cost. If not, the tariff level has to be increased up to the point where the revenue and O&M cost balance each other. A higher tariff level would result in fewer consumers and less capacity, and thus a lower O&M cost. The optimization of the system configuration needs to be a part of this process since an integration of various locally available resources, such as solar, wind and biomass, would minimize capital and O&M cost under a certain load requirement in comparison to a single-resource system.

Table 1
Profile of Kaylapara village (Census 2001).

Number of households	619
Total population	3,537
Total area available for cultivation	169 ha
Total area of the village	358 ha

Table 2
Details of 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	3 km: three phase, 400 V
Number of beneficiaries	Approx. 200
Month of commissioning	March, 2006

Table 3
Tariff structure for Users of Kaylapara PV power plant.

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

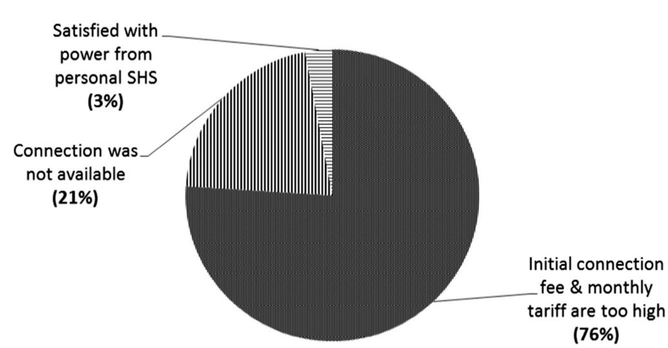

Fig. 2. Reasons for not connecting to the micro-grid.