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Original Research Article

Techno-economic sizing of off-grid hybrid renewable energy system for rural electrification in Sri Lanka

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ABSTRACT

Off-grid hybrid renewable-energy-based power systems for rural electrification have become an attractive solution for areas where grid electricity is not feasible. Hybrid energy systems use several energy technologies, and the selection of proper technologies with optimum sizing of the selected components has become very important. The objective of this study has been to investigate the optimum configuration of a hybrid system that can supply electricity to a rural community in Sri Lanka. A rural village in Siyambalanduwa (Sri Lanka) comprising approximately 150 households with a resultant daily electricity demand of 270 kWh and a nighttime peak of 25 kW has been studied. This region receives abundant solar irradiation with an average of 5.0 kWh/m^2/day. In addition, the annual average wind speed of this region is 6.3 ms^{-1}, which results in a wind power density of 300 W/m^2 at 50 m above the ground. The total net present cost of configuration has been calculated for 20 years of the system lifetime to examine the lowest energy cost option. The combination of wind turbines, photovoltaic (PV) system, a battery bank, and a diesel generator has been found to be the optimum hybrid system with the corresponding capacities of 40 kW, 30 kW, 222 kWh, and 25 kW. This system can supply electricity at an approximate levelized cost of 0.3 $/kWh. It has also been found that the optimized system can supply the demand with the change in energy costing no more than 0.1 $/kWh, although the annual average wind speed varies in the range of 4.5–6.3 ms^{-1}. Consequently, the influence of changes in the annual average solar irradiation ranging from 4.0 to 5.5 kWh/m^2/day on energy cost has been found to be negligible. The energy cost of the project has also been analyzed, considering the off-grid operation of hybrid systems for the first 10 years and the grid-connected operation for the next 10 years. The hybrid system has been found to be economically viable whether it was operated off-grid or connected to the grid.

Introduction

Being a small island with abundant sunlight year-round and substantial wind resources in most regions, Sri Lanka has become an ideal location for developing renewable-resource-based energy systems. Currently, the electricity generation system in Sri Lanka comprises 40.5% of hydropower, 49% of thermal power, and 10.5% of renewable energy (mini hydro, bio-energy, wind, and solar) [1]. However, in dry seasons, the contribution of the thermal power stations, which are based on fossil fuels, increases up to 70% due to the reduction in generation from the hydropower stations. Sri Lanka does not have any fossil fuel resources, therefore requiring such resources for these thermal power stations to be imported. It is a well-known fact that the price of fossil fuels is increasing day by day while resources are depleting. In addition, the greenhouse gas emission from burning fossil fuel causes severe environmental impact. However, the global market for renewable energy technologies is growing rapidly, and the price per watt installed for photovoltaic (PV) and wind systems is decreasing over time because of advancements in technology and mass production. Hence, currently, the most viable energy sources for Sri Lanka are the renewable sources.

The Ministry of Power and Energy in Sri Lanka has set a target of achieving 100% electrification rate within the coming few years, resulting in proposals for new power plants, grid expansion, and rural electrification projects, some of which have already commenced. The proposal also highlights the objective of increasing the share of nonconventional renewable energy from 4.1% in 2007 to 20% by 2020 [1]. To achieve these objectives, the government has taken necessary initiatives to promote off-grid renewable energy technologies and national grid expansion for rural electrification.

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In this situation, a micro-grid powered by renewable resource-based hybrid systems can be considered for rural electrification, which has drawn the attention of the government recently [1]. However, until today, this topic has not been studied in Sri Lanka, although hybrid systems are relatively popular in other South Asian countries such as India [2,3], Bangladesh [4], and Nepal [5,6], despite having a high rate of household electrification [7]. As the population in rural areas in Sri Lanka is relatively low, electrifying the community with on-site generation, instead of transmitting power from a power station located very far, would be an economically attractive solution.

The main limitation of renewable energy systems is that they cannot provide reliable electricity owing to their intermittent nature [8]. Hence, energy storage is an essential element in off-grid hybrid energy systems to maintain the continuity of supply and to stabilize the power fluctuations in renewable systems [9,10]. Several sources can be used to mitigate the variations in power generation as well as reduce the size of the storage system [11]. For example, because the sun shines during daytime while wind mostly blows at night, PV and wind can make a better energy system together. Other than renewable energy systems, diesel generators are also widely used in off grid-hybrid systems to manage the power system stability and load, and also to improve the reliability of the supply [12,13]. In addition, a significant reduction in the system cost can be expected using this kind of a conventional source in combination with renewable sources.

The most important criterion in designing off-grid hybrid systems is that they must be economically attractive, while providing a reliable supply of electricity for rural consumers. The combination of generation sources, components, and their capacities selected for the hybrid system have a great influence on the system cost, its lifetime, and the affordability of the service to the end users. Therefore, correct sizing of system components is crucial in the design of a hybrid system.

The impact of grid expansion on the system economy also has to be considered in the design stage of an off-grid energy system. This is because the grid might be expanded to the considered area during the effective lifetime of the off-grid system, possibly resulting in negative consequences for entrepreneurs, as discussed in Ref. [14].

Several approaches based on numerical methods have been discussed in the literature for achieving the optimal configurations of the hybrid systems. The component sizing vector must be solved, which is the minimum total net present cost of the system subjected to constraints such as minimum state of charge (SOC) of the battery bank and capacity shortage. The genetic algorithm has been used for solving the above problem in Refs. [15,16], whereas the particle swarm algorithm has been used in Refs. [17–19]. The DIRECT (Dividing RECTangles) algorithm has been used in Refs. [20,21]. The accuracy of the result and the number of possible combinations that can be considered for analysis depend on the method used to minimize the objective function. With the increasing interest in micro-grids, several commercial software have been developed for evaluating different aspects of hybrid energy systems, for example, HOMER, Hybrid2, RETScreen, iHOGA, Hybsim, and HySys [22].

In this work, we investigated the techno-economically optimum size of an off-grid hybrid energy system for electrifying a rural community in Sri Lanka using the HOMER software. The levelized cost of energy (LCOE) of the system has been determined, and the robustness of the results has been investigated for changes in the resource potential, load, and the cost of the system components. Later, we investigated the economic impact of connecting the hybrid system to the grid.

Data collection

Several rural regions in Sri Lanka do not have access to electricity but an abundance of solar and wind energy. Although solar home systems (SHSs), small wind turbines, and micro-grids powered by micro/pico-hydro, dendro, or biogas power plants are in operation in some of the rural regions, attention on hybrid energy systems in Sri Lanka is not significant [23].

In Sri Lanka, the Ceylon Electricity Board (CEB) is the authorized body for the supply of electricity. Recently, CEB announced a list of villages that will not obtain grid access in the near future, therefore prompting the Ministry of Power and Energy to instruct the sustainable energy authorities to take necessary measures to provide off-grid renewable energy solutions to these households [23]. A total of 1072 villages are included in this list, accounting for 37,800 households in different parts of the country. In this study, we considered the Monaragala district in the Uwa province, with 258 villages that will not get grid electricity in the near future, for investigating the techno-economics of a hybrid energy system due to its low electrification rate and the relatively better potential of solar and wind resources. It is one of the poorest regions in Sri Lanka with a population of approximately 0.5 million, whose income is derived mainly from agricultural activities [24]. Many villages in this district do not have access to electricity, and they are located far from the urban centers of the region. Some villages of the Siyambalanduwa Divisional Secretariat (DS) are similar examples. This DS consists of 48 villages with a total population of 55,300, accounting for 13,600 households. Of the total number of households, 5750 households do not have access to electricity [25]. One of the villages from the Siyambalanduwa DS, located at 6.76° N latitude and 81.54° E longitude, has been selected for detailed study.

Village load profile

A village consisting of about 150 families has been considered. The hypothetical load profile of the village has been derived referring to the load profiles available on the Internet for different rural electrification projects implemented in developing countries [26–28], as primary data collection was not conducted, and it was based on the following assumptions:

- The village consists of 10 rich families, 50 medium-income families, and 90 low-income families. This assumption has been made because the poor constituted the highest percentage of the people living in Siyambalanduwa.
- The village consists of a community center, temple, preschool, primary school, 2 shops, streetlights, and two rice mills, which consume daily electrical energy of about 60 kWh.
- Wealthy families use electrical appliances, mainly bulbs, color television, cassette and DVD player, fans, refrigerator, water heater, water pump, computer, and an iron. Electricity is not used generally for cooking in rural villages of Sri Lanka. Instead, firewood is used, because it is widely available at zero cost. The daily energy consumption of this type is assumed to be 4 kWh.
- Medium-income families use electrical appliances such as bulbs, radio, television, water heater, and an iron. The daily energy consumption of a medium-income family is assumed to be 2 kWh.
- The daily energy consumption of low-income families is very low. They use electricity only to fulfill basic requirements such as lighting, communication (radio and television), and perhaps ironing of clothes. Families in this category have very small