Journal of Cleaner Production 206 (2019) 508–523

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Enabling private sector investment in off-grid electrification for cleaner production: Optimum designing and achievable rate of unit electricity

M. Mujahid Rafique [a, b, *], Haitham M.S. Bahaidarah [b], M. Khalil Anwar [c]

[a] Faculty of Mechanical Engineering, TU Bergakademie Freiberg, Germany
[b] Department of Mechanical Engineering, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia
[c] Department of Mechanical Engineering, University of Management & Technology, Lahore, Pakistan

ARTICLE INFO

Article history:
Received 7 June 2018
Received in revised form
4 September 2018
Accepted 14 September 2018
Available online 21 September 2018

Keywords:
Solar energy
Off-grid PV
Sustainable development
Zero energy communities
Developing countries
Pakistan

ABSTRACT

The electrification rate and unit rate of electricity are important factors for economic and social development; especially in developing countries. The supply of electric power at low rates can help in setting ambitious targets to expand the reach of electricity to remote rural areas. The private or local investment to build isolated microgrids could be a cost effective and technically viable solution to extend the electricity access in different countries. However, country specific feasibility studies are required which can help to estimate the required investment and life cycle expenditures. In this paper, an algorithm has been presented for optimal sizing and life cycle cost analysis of an off-grid solar PV system. As a case study, an off-grid PV system is designed to build a zero energy community in five capital cities of Pakistan in order to access the feasibility and potential of off-grid power systems throughout the country. Furthermore, life cycle cost analysis of designed PV system has been carried out in order to determine the unit cost of electricity. The results of economic model show that, the installed PV system can provide electricity at an average rate of 0.082 US$/kWh for all cities with a minimum rate of 0.076 US$/kWh achieved for Quetta whereas; cost of conventional electricity varies from 0.15 to 0.20 US$/kWh in Pakistan. It can be concluded that, installing an off grid PV system in Pakistan is viable both technically and economically. The produced electricity is 45–58% cheaper than the conventional electric power supply used in the country. This study can be used as a benchmarking and guideline to design off-grid PV power systems for other facilities and locations with estimated load demands.

1. Introduction

The access to high quality electricity at affordable rates is an important factor for development of modern societies. Low electrification rate in developing countries is a major barrier to economic and sustainable development. The wider access to electricity can pose many positive benefits such as increased economic opportunities, better life quality, better health and improved educational facilities. The lower electrification rate in rural communities as compared to urban areas is also a major cause for regional developments within the countries. These disparities in regional development is causing an increase in migration from rural to urban areas in developing countries and thus putting stress on urban infrastructure. Because of these reasons, access to electricity has taken greater prominence in recent years on the global development agenda.

Pakistan is among those developing countries which are facing severe shortages of energy nowadays. About 51 million people in Pakistan live without electricity and more than 30% areas are still to be electrified (Fig. 1). Among un-electrified areas, rural communities share major portion as these are far away from the central grid. In Pakistan, the electricity is mainly produced from imported fossil fuels. About 70% of the total electricity is produced using oil, gas, and coal. The consumption of these fossil fuels is increasing at a rapid rate because of increasing demand of electric power in the country, as shown in Fig. 2 (PCRET, 2018; Rafique and Rehman, 2017). The electric power demand is increasing at an annual rate of 8% whereas; generation pace of electricity is not matching this

* Corresponding author. Faculty of Mechanical Engineering, TU Bergakademie Freiberg, Germany.
E-mail address: mujahidrafique89@aol.com (M.M. Rafique).

https://doi.org/10.1016/j.jclepro.2018.09.123
0959-6526/

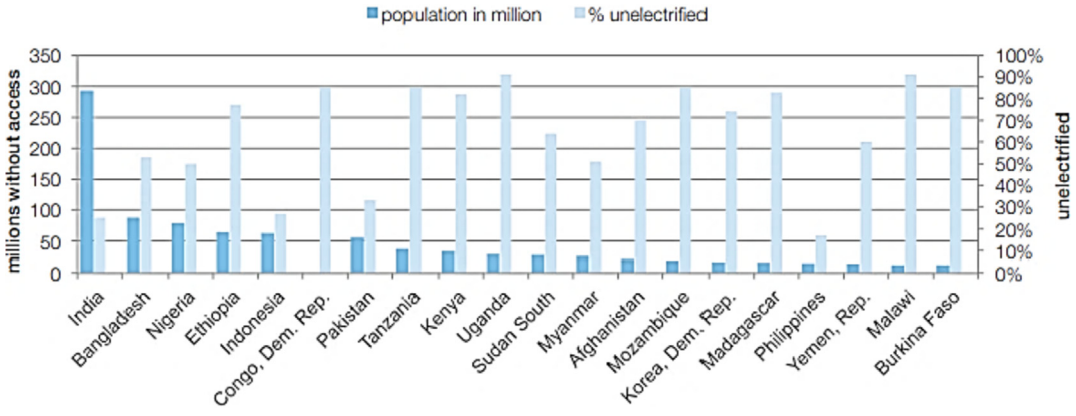

Fig. 1. Access to electricity in developing Asia. Source: IEA, World Energy Outlook 2016–17.

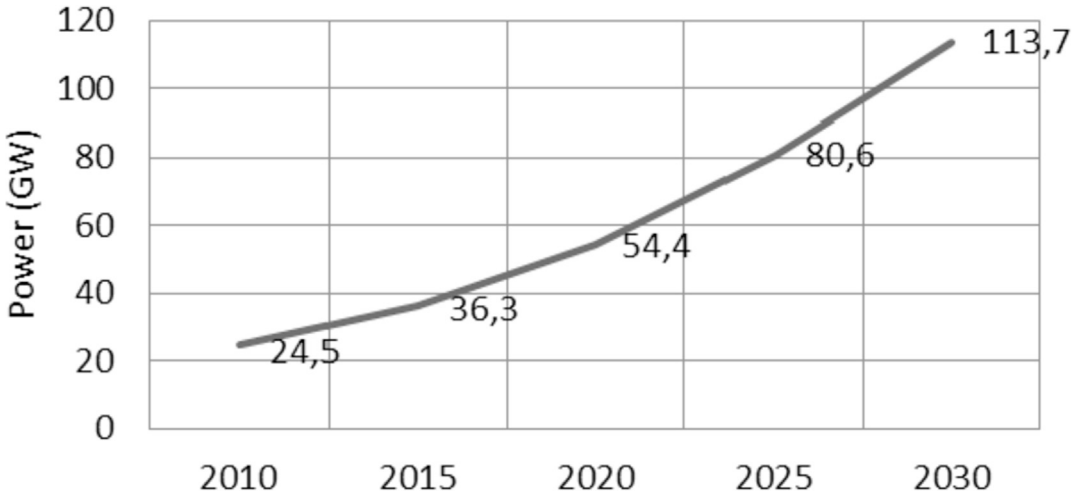

Fig. 2. Electric power demand in Pakistan (Rafique and Rehman, 2017).

increasing demand of power in the country causing a shortfall of about 5000–5500 MW. The ever-widening gap between supply and demand of electricity is one of the greatest hurdles in the current economic growth of Pakistan. Due to these energy shortages, the urban areas are facing 8–10 h of load shedding while 10–12 h of load shedding is very common in rural areas. Furthermore, the energy sector is under high pressure due to rapidly diminishing domestic gas reserves which are the second major contributor to national power generation.

The soaring demands of Pakistan's energy sector are met by oil, natural gas, coal, and liquefied petroleum gas (LPG). The increasing use of these imported fossil fuels for electricity generation puts an extra burden on national exchequer and the country is in a grip of severe scarcity of energy. Furthermore, the use of fossil fuels for power generation is causing an increase in the emission of greenhouse gases in the country at a rapid rate (Rafique et al., 2018). It is projected that the emission of CO_2 will reach an amount of 4621 million tons equivalents till 2050 which shows that Pakistan is on the path of environmentally damaging energy mix. These emissions have many direct and indirect effects of climate change on public health. According to the World Health Organization, about seven million people died in 2012 as a result of air pollution.

Despite all above mentioned energy related concerns, the country is blessed with abundance of solar energy potential which can be exploited to address these issues. Geographically, Pakistan is situated in the area which receives high intensity of solar radiation as compared to many European and North American countries (Rafique et al., 2018). The sun shines throughout the year and can fulfill the power demands of individuals and communities, if harnessed efficiently.

To overcome the present national energy shortfall it is now necessary to develop and utilize solar PV and solar thermal technologies to generate power and contribute towards total national energy portfolio. The major issue and hurdle for the development of solar technology in the country is its high initial cost and lack of community knowledge about its long term benefits. From literature, it has been noticed that, there is a lack of research work related to real on-time electricity rates from solar PV technology according to actual market pool and tariff prices for climatic conditions of Pakistan. In addition, oversizing and incorrect design of solar PV module, back up battery, and other associated components increase the total cost of integration of solar energy technology to the community. Therefore, optimal sizing of an off-grid solar system for a specific site according to its climatic conditions is crucial to ensure the economic feasibility and technical reliability of such a system. The lifelong based economic analysis and correct sizing of the system components could be a beneficial solution in long run. In this way, the proper design and knowledge of its long term benefits can help in promoting solar technology in Pakistan and other developing countries.