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Rural electrification and expansion planning of off-grid microgrids

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ABSTRACT

This paper presents the past and current practices for rural electrification and the current trend in using off-grid microgrids to provide energy to the customers with no access to the central electricity network. The challenges correspond to the capacity expansion of off-grid microgrids including the financial and business models for establishing these technologies, the economic and reliability considerations, the environmental issues, the expansion and feasibility studies, and the uncertainties in the operation horizon were presented.

1. Introduction

A microgrid is one of the most indispensable elements of smart power systems to improve the reliability and resilience of energy supply in distribution networks. A microgrid is a group of interconnected distributed generation and demand entities within the clearly defined boundary to represent a single controllable entity in the utility that operates either in grid-connected or island mode. The generation capacity of microgrids ranges from kilowatts to megawatts and these small power systems are built for a variety of applications, from small cell phone towers (also referred to as nanogrids) to large commercial, industrial, and military facilities. In developed countries, microgrids are used to improve energy security, power quality, reliability, and resilience. The declining capital cost of renewable resources and energy storage promotes the application of such technologies to provide electricity for households and small communities. Several countries, including Australia, Italy, Denmark, Spain, and Germany, are expected to have greater residential loads served by renewable resources. In recent years, the merits of developing grid-connected microgrids to improve reliability and resilience measures in critical infrastructure systems (e.g. hospitals, industrial facilities, universities, and military bases) have become more widely understood compared to off-grid microgrids. The effects and objectives of implementing microgrids for off-grid electrification are quite different from the cases in which microgrids are operated in grid-connected mode and the utility grid is counted as the primary source. Off-grid microgrids mainly provide access to electricity for people who live in areas for which an extension of the grid cannot be performed with reasonable time and cost. Therefore, the impact of off-grid microgrids is not only measured by the reduction in the electricity cost in rural and remote areas, but also by the extent of improvement in residents' quality of life. It is estimated that 1.18 billion people (17% of the world's population) have no access to electricity. This includes 512 million people in Asia, 244 million in India, 41 million in Indonesia, and 11 million in the Philippines (WEO, 2016). For the developing world, providing and maintaining access to the electricity is the main driver for developing off-grid microgrids, as this technology provides the most economical solution for electrification of remote areas. In fact, microgrids could become an alternative to grid extensions if the decrease in cost trends persists.

2. Market and business model for off-grid microgrids

The microgrid market is expected to reach 38.99 billion by 2022, with a compound annual growth rate of 12.45% in 2016–2022 (Microgrid, 2017). Remote/off-grid microgrid solutions are expected to claim a considerable portion of the total microgrid market, with annual revenue for off-grid energy supply (microgrids and nanogrids) expected to exceed $25 billion by 2024. The markets for residential and commercial applications, including healthcare, rural electrification, and telecommunications, are expected to grow at a considerable compound annual growth rate in 2016–2022 (Microgrid, 2017). The growing market for off-grid microgrids for remote and rural electrification is supported by organizations such as the United Nations and World Bank.

Off-grid microgrid projects promote the participation of other players besides governments (e.g. private-sector businesses or individuals, non-government or community-based establishments) with corresponding human and monetary resources and reduce the pressure on utilities to extend services to remote areas. In order to increase the installed capacity of off-grid microgrids, a system of incentives should be developed to attract investment. The geographical location, capacity and scale, the income portfolio of the consumers, and the available subsidies are major factors that impact the investment decisions of private investors and operators. Since off-grid microgrids in remote and inaccessible areas may not entice private-sector interest, the entities

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that organize the community are usually the owners or operators of these systems. These entities are responsible for the operation, expansion planning, and maintenance of generation and distribution assets as well as managing the related financial services (e.g. tariff collection). The business model for off-grid microgrids involves devising tariffs that consumers are willing to pay and subsidies for capital costs to guarantee a reasonable rate of return for the investment and operation costs. A common approach to promoting this technology is to subsidize a considerable share of the capital cost (e.g. 15–20% in micro-hydro grids in Sri Lanka) by the government through funding rural electrification projects while the community of private investors usually covers maintenance and operational costs. Another approach leveraged by utilities or energy service companies that usually own the facilities is to operate the off-grid microgrids and regulate the fees for service to be comparable to rural grid tariffs paid by the customers. In order to adjust the off-grid electricity tariffs, the utility or energy service company provides subsidies for capital costs and a portion of operational and maintenance costs using public funding sources. This model is widely adopted in (1) China to operate 10–150 kW photovoltaic (PV) microgrids; (2) isolated diesel generator projects in the Philippines, and (3) the Renewable Energy for Rural Markets Projects in Argentina.

3. Global statistics of off-grid microgrids

In developing countries, the market for off-grid microgrids is mainly focused on enhancements in electrification rates. In 1990–2010, rural electrification improved with the increase in population by 300 million people during the last two decades. Therefore, the number of individuals with no access to electricity has not changed. In India, the Philippines, and Indonesia, the growth rates for grid electrification is 2% annually. However, the geographic conditions of highly populated remote areas with limited access to electricity such as northern India, Indonesia, and the Philippines impedes expansion of central utility grids. In this section, the current state of major off-grid microgrid developments in the world is presented.

3.1. China

China has the largest population in the world, 1.375 billion people, with almost 50% living in rural areas. The geographical characteristics of the country and the considerable rural population makes rural electrification a critical and challenging task. Rural electrification in China went through three major phases. In the first phase (1949–1977), government efforts were mainly focused on large commercial energy developments for urban areas and industrial facilities and rural areas were supplied by small thermal plants and hydro units. The second phase (1979–1997) brought a major reform in rural power management that promoted investment decisions by counties, a strategy that brought the electrification rate to 99%. In the last phase of development, which began in 1998, the central grid has been extended to reach rural areas formerly served by off-grid resources. By 2011 China achieved 99.6% rural electrification, though that still left 3 million people mostly living in remote areas of western China with no access to electricity. The high altitude, rugged terrain, harsh weather conditions, and sparsely distributed population in these areas makes grid extension extremely costly. The Brightness program in 1999–2002 was the first effort by the government to promote solar PV generation technology and hybrid PV/battery systems to serve 50,000 people in western China. The Township Electrification Program in 2002–2005 increased the capacity of solar PV, PV/wind hybrid systems, and small hydro stations to serve 1 million people in western China. The Village Electrification Program in 2005–2010 with the participation of international, national and local agencies, resulted in the development of 400,000 off-grid solar home systems in 20,000 villages in western China. By 2013, the capacity of grid-connected and off-grid microgrids with diesel, hydro and solar PV systems was increased and the installed capacity of solar PV off-grid microgrids reached 500 MW. By the end of 2015, China aimed to provide power to 1.19 million people without electricity by using solar PV technology.

3.2. India

India is a leading country in developing grid-connected and off-grid microgrid applications. Microgrid growth is supported by India's aggressive policies backing electric vehicles. Electric vehicles' batteries play a significant role in storing solar energy. The Indian government is seeking to develop a financial model for "EV as a service" to promote using EV batteries as a grid source. Several programs were initiated by the government to develop off-grid microgrid projects and grid extensions that target bringing electricity to one-quarter of India's population still without it. India is in the midst of a major program to connect 250 million people without access to the grid, while improving conditions for others throughout the country who face power shortages. The Deen Dayal Upadhyaya Gram Jyoti Yojana rural electrification program will supply power to 18,452 villages by 2018, with 4248 villages served by off-grid microgrids. In the State of Karnataka, the SELCO Foundation deployed DC microgrids with solar-storage technologies to supply energy to Baikampady Mangalore, Mendare Village, Neelakantarayanagaddi Village, and Kalkeri Sangeet Vidyalaya. The major policy of the Jawaharlal Nehru National Solar Mission (JNNSM) is to promote solar energy in off-grid microgrid deployments. Distributed renewable energy projects using the wind, hydro, biomass generation technologies, and hybrid systems have been established to meet the energy demands of isolated communities. As of June 2013, the physical progress of electrifying remote villages program showed that 10,154 villages and hamlets were supplied with the electricity and 12,771 villages and hamlets were sanctioned (Remote Village Electrification Program, 2013). India has 164.7 MW biomass gasifiers for rural off-grid and industrial applications, 174 MW solar PV, 2.25 MW small wind generation and hybrid systems, 13.2 MW of small hydro plants and 3.77 MW of biogas systems. The Indian Ministry of New and Renewable Energy drafted a national policy to add up to 500 MW of microgrid capacity within the next five years. The policy promotes forming local communities to address the current challenges for collecting tariffs and dispute resolution, as well as determining regulations for selling electricity to the local utilities.

3.3. The Philippines

The installed capacity of diesel microgrids is 375 MW, with most of these microgrids operating six to eight hours per day. The operating capacity in most microgrids is less than 500 kW. The power corporations in the Philippines aim to electrify rural areas using off-grid microgrids. A study by the World Bank in 2002 (Rural Electrification and Development, 2002) showed the substantial socioeconomic benefits gained by serving a typical rural household from the utility grid in the Philippines, as shown in Table 1. The objective of the Rural Power Project (RPP), which was supported by the World Bank in partnership with the private sector, was to provide adequate, reasonable, and

Table 1
Quantified benefits of electrification for a typical household in rural areas of the Philippines (Rural Electrification and Development, 2002).

Benefit Category	Benefit Value ($/month)	Consumer Type
Expanded use of lighting	36.75	Household
Expanded use of radio and television	19.6	Household
Returns on education and wage income	37.07	Wage earner
Time saving for household tasks	24.50	Household
Productivity of home business	34 (current) 75 (new)	Business