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Sustainability and design assessment of rural hybrid microgrids in Venezuela

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A B S T R A C T

Nowadays, 1.2 billion people lack access to electricity, mainly in rural areas of developing countries. In particular, 22 million people do not have electricity in Latin America and many governments are developing rural electrification programs to deal with this situation. Off-grid hybrid microgrids based on renewable energy are an efficient option for providing dispersed rural populations with access to electricity. However, microgrids are still a minority option, as governments of developing countries generally consider them expensive and not effective. In this context, the evaluation of projects based on hybrid microgrids is required in order to improve the knowledge about these technologies. In this paper, 13 microgrid projects in north-western Venezuela are presented and their environmental, technical, socioeconomic and institutional dimensions of sustainability are evaluated. For this purpose, an evaluation methodology based on some ad hoc criteria is developed, assessed by means of technical visits, semi-structured interviews and 106 surveys of technical operators and beneficiaries. The results show that microgrids can satisfy the energy needs of the population, while promoting technological change towards the use of more sustainable technologies. In addition, the key aspects for strengthening projects' sustainability are highlighted.

1. Introduction

Nowadays, 1.2 billion people lack access to electricity in the poorer rural areas of developing countries. In Latin America, 22 million people do not have electricity [1]. In these regions, given the dispersion of houses and the long distances to urban centres, the national electricity grid extension or the fuel supply for diesel gensets are not economically profitable [2]. Consequently, off-grid systems based on renewable energy technologies (RET) become an effective strategy for electricity access and poverty reduction, while reducing greenhouse gas emissions [3]. Indeed, the use of renewable energy has progressively increased, and 300 million people obtained access to electricity by means of off-grid RET-based systems from 2007 to 2016 [4]. Solar photovoltaic (PV) panels are the most common option, representing almost 50% of the total RETs for rural electrification [5], mainly through solar home systems (SHS) [6]. However, according to Hosseinalizadeh et al. [7] and Kaldellis et al. [8], wind energy can be also profitable and appropriate in regions having wind or wind and solar resources.

Off-grid systems may provide electricity through stand-alone home systems or microgrids (generators supplying electricity to several consumption points via a small network) [3]. Although stand-alone home systems are widely used, microgrids can be more profitable and reliable according to the distribution of houses [9]. When relying on more than one renewable energy source (RES), for example, wind and solar, the hybrid microgrid concept is commonly used, and both RES lead to a more reliable supply [10]. In fact, hybrid wind-PV microgrids can provide end-users with an even better service quality than that of conventional fuel-based technologies [3]. However, the long-term sustainability of hybrid microgrid projects is still an issue [11].

In order to improve sustainability [12], key aspects from project failures or successes should be identified and the quantity and quality of information provided to decision-makers must be increased [13]. Despite the large amount of rural electrification projects implemented in developing countries, very few empirical evaluations analysing the factors that influence the success and

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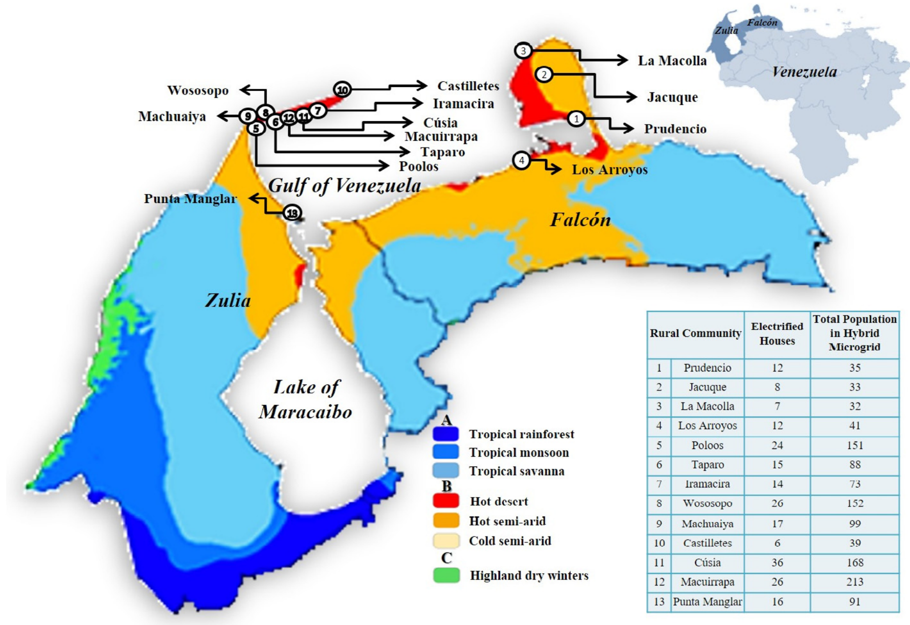

Rural Community		Electrified Houses	Total Population in Hybrid Microgrid
1	Prudencio	12	35
2	Jacuque	8	33
3	La Macolla	7	32
4	Los Arroyos	12	41
5	Poloos	24	151
6	Taparo	15	88
7	Iramacira	14	73
8	Wososopo	26	152
9	Machuaiya	17	99
10	Castilletes	6	39
11	Cúsia	36	168
12	Macuirrapa	26	213
13	Punta Manglar	16	91

Fig. 1. Hybrid microgrid locations in north-western Venezuela, within the Köppen climate map [26].

sustainability of small-scale projects have been published [14]. There are very few empirical evaluations of community RET-based projects assessed in situ several years after their installation [15].

The three basic dimensions of sustainability were established in 1987 [16]: economic, social and environmental [17]. Later, Ilskog et al. [18] maintained those three dimensions, calling the social aspect socio-ethical and adding two more: technical and institutional. Most studies have a clear focus on technical and institutional aspects, such as mentioned by Yadoo [19] and Schillebeeckx [20], while fewer consider the relevance of social and economic factors for the sustainability assessment [17]. A single socioeconomic dimension is considered in this paper, as the economic and social dimensions are related. Therefore, 4 dimensions for the sustainability assessment are proposed: environmental, technical, socioeconomic and institutional. The four dimensions are evaluated through some ad hoc specific criteria which can be assessed by end-user surveys, technical visits, simulations or other adequate tools. The definition of the criteria was made together with technicians from the Electricity Ministry of Venezuela. The proposed criteria are sufficiently robust and flexible to be easily used in other contexts, regions and countries [18]. Therefore, the four dimensions are valid for the evaluation of rural electrification projects in any context, only adapting the way that each criterion is assessed to accord with the specific conditions of each case study.

In this context, the main contribution of this paper is the evaluation of 13 hybrid microgrids in Venezuela, implemented within the "*Sembrando Luz*" ("Sowing Light") program [21]. For this purpose, a comprehensive evaluation methodology is developed, which may be applicable to programs and/or specific RET-based rural electrification projects in developing countries. The methodology considers the 4 aforementioned sustainability evaluation dimensions: environmental, technical, socioeconomic and institutional. The information required for the evaluation is gathered from surveys of end-users, interviews with technical and community leaders, historical record data and simulations using HOMER. Results show the key elements for the long term sustainability of the projects, from the microgrid design to their implementation, and are useful for the next 149 hybrid microgrids the Venezuelan government has planned to install [22].

The remainder of the paper is organised as follows. In Section 2, the technical aspects, the design process and the generation technologies used in the microgrid projects in Venezuela are described. Section 3 presents the evaluation methodology, while Section 4 explains the results obtained for each sustainability dimension, based on the criteria defined. In Section 5, the results for the 4 dimensions are discussed. Finally, the main conclusions are summarised in Section 6.

2. Design description of hybrid microgrids in Venezuela

The design and implementation of hybrid microgrids is one of the electrification strategies within the "Sowing Light" program, developed by the Venezuelan government [21]. To date, 18 microgrids have been installed; the first 13 in northwest Venezuela, 4 in communities in Falcón state and 9 in Zulia state (Fig. 1). In Falcón the communities are composed of Creoles [23] whereas in Zulia the population belongs to the Wayuú ethnic group [24]. The indigenous population in Venezuela are a small minority, usually located in dispersed rural settlements with low access to education, health and information services, which influences their socioeconomic development [25].

In the following sections, the sizing and standardisation of hybrid microgrids in north-western Venezuela is described (Section 2.1), as well as the wind and solar generation technologies (Section 2.2), the diesel backup and the battery storage (Section 2.3). Finally, the microgrid structure and control strategy (Section 2.4) and the management model (Section 2.5) are detailed.

2.1. Hybrid microgrid sizing and design standardisation

The estimation of the average daily consumption was carried out by Fundelec (Ministry of Electric Energy of Venezuela). The estimation was based on historical data obtained during the national censuses carried out by the National Institute for Statistics of Venezuela (INE), in previously electrified rural houses. Moreover, Fundelec carried out surveys in rural areas to be electrified in order to profile the houses and inhabitants. Thus, a typical list of house appliances and their use was generated (Table 1). In this way,