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# Lifetime, cost and fuel efficiency in diesel projects for rural electrification in Venezuela

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ABSTRACT

From 2000–2016, 600 million people in developing countries accessed electricity through fossil-fuel-based technologies, both in isolated and grid-connected schemes. Although an increase in the use of renewable energy sources is expected, 40% of the new connections until 2030 will be through conventional technologies, including diesel. Diesel generator sets can be carried out using three different strategies: (1) off-grid, (2) support to national grid extension or (3) support to distributed generation plants in rural zones. Advantages and inconveniences of each strategy have not clearly been stated yet. The objective is to evaluate and compare the 3 strategies to improve future projects. Therefore, cases from Venezuela have been studied. Historical generation and operational data are analyzed, as well as in situ visits, surveys and interviews. Although Venezuela is an oil producer country, contrasts with the world energy matrix since its fossil fuel-based generation is less than a half of the global average. Results show the advantages of each strategy are conditioned by geographical, climatic and logistical factors, while benefits of the support to national grid extension strategy have been highlighted. These results can assist rural electrification promoters to effectively determine the most appropriate diesel projects strategy.

## 1. Introduction

Between 2000 and 2016 the number of people without access to electricity fell from 1700 to 1100 million worldwide (IEA, 2017). Until 2012, 71% of the electrification in the world was carried out by grid extension and using fossil fuels: 45% coal, 19% natural gas and 7% diesel and other petroleum derivatives. Since 2012, isolated systems and mini-grids have increased their share, achieving 6% of the new electrifications, while diesel generator sets (gensets) have represented 22% of these projects (IEA, 2017). In fact, in order to achieve universal access to electricity in 2030 (United Nations, 2015), the use of diesel technology is expected to increase in the poorest regions of developing countries (Narula et al., 2012). Although the proportion of fossil fuels within the generation mix will be reduced, the number of rural electrification projects based on such technology will still be very significant (IEA, 2017).

Most of the rural electrification programs in developing countries are based on grid extension (Haghighat et al., 2016). However, distributed generation (DG) technologies are being increasingly used (Carley, 2009; Paliwal et al., 2014). In particular, the use of isolated and micro-grid systems has increased (ARE, 2014), including grid-connected and off-grid gensets (Mainali and Silveira, 2013). In 2017, around 380,000 diesel generation units were purchased in developing countries (Bloomberg, 2017). In Africa, despite the growth in photovoltaic (PV) and hybrid wind-PV systems, most rural electrification projects are based on diesel generators (APP, 2017). In Southeast Asia, grid-connected and off-grid generator sets will allow 29 million people to access electricity from now until 2030 (IEA, 2017). In Afghanistan, since 2010, 1310 diesel-based facilities have been installed (Mainali and Silveira, 2013). In Latin America, Brazil has electrified a large part of the Amazon with diesel generators due to their low investment costs (Slough et al., 2015), a consolidated fuel supply chain and a subsidy system for diesel purchase (Fuso Nerini et al., 2014). In Colombia, 73% of the territory is isolated from the grid and supplied by diesel generators (UPME, 2014). In Cuba, 40% of the power generation comes from fossil-based generators, both grid-connected and off-grid (Suárez et al., 2012).

The most controversial issue regarding diesel-gensets is the environmental aspect (Strachan and Farrell, 2006), given the emission of greenhouse gases (GHG) and the impact on the community's ecosystem

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(US EPA, 2017). However, the increase in GHG emissions caused by diesel-gensets and other thermoelectric technologies in new electrification projects will be only 0.2% by 2030 (IEA, 2017). In addition, the emissions will be balanced by a reduction of 165 $MtCO_2$ in methane and nitrous oxide emissions, thanks to the replacement of biomass for cooking and lighting (IEA, 2017). Moreover, in global terms, the initial investment in diesel-based rural electrification projects is lower than in those based on renewable energy technologies (Haghighat et al., 2016; Banal-Estañol et al., 2017). Yuan (2015), states that diesel-gensets have prevailed in rural electrification basically due to their low initial costs (Cid-Serrano et al., 2015), as well as the easy configuration and operation (Lahimer et al., 2013). Sayingh Khennas and Barnett (2000) claims that such predominance is caused by high subsidies to fossil fuels, particularly in developing countries. However, the main advantages of diesel-gensets are that they do not require renewable energy resource evaluations before installation and that they can be located anywhere (López-González et al., 2017b), without needing storage or backup technologies (Bureau and Growth, 2004). Thus, only an accessibility study is required to guarantee the periodic fuel supply (Szabó et al., 2011).

Among the diesel-based rural electrification projects, three strategies are usually employed: (1) off-grid, isolated diesel-gensets not connected to the grid (Khodayar, 2017); (2) support to national grid extension, diesel-gensets installed at the end of a rural distribution network; and (3) support to distributed generation, with diesel-gensets installed in small DG grids operating as peaking power plants. In order to identify the most appropriate strategy, the ex-post evaluation of experiences is fundamental, a few years after project implementation. Thus, the key issues to be improved in future projects can be identified, to optimize the economic resources and the efficiency of fuel consumption (Kyte, 2017). In this sense, a greater amount of in-situ research is required for rural electrification projects (Terrapon-Pfaff et al., 2014).

In this context, the main objective of this work is to evaluate and compare the lifetime, cost and fuel efficiency of the 3 diesel-based strategies. More specifically the aim is to identify the operational performance, as well as the advantages and limitations of each strategy, to assist rural electrification promoters in the efficient implementation of projects. To do so, real case studies from Venezuela, are evaluated. In contrast with the world energy matrix, supported by fossil fuels in more than 71% (IEA, 2017), in Venezuela only 36% comes from this type of polluting sources (MPPEE, 2013). Indeed, 64% of electricity is generated from hydroelectric power plants, doubling the global average of generation from technologies with low greenhouse gas emissions. “More specifically, the case studies analyzed in this paper are implemented within the national "Energy Revolution" program, implemented between 2008 and 2013. This program covers the energy generation and consumption in rural and poor areas of Venezuela. With regards to generation, diesel gensets have been installed through 90 projects in rural areas to expand the electricity coverage in these regions. With regards to consumption, 6,867,383 bulbs have been replaced throughout the national territory, with a reduction in the national peak demand of 172 MW (around 1–2% of the global consumption). In addition, several educational talks have been organized in rural and indigenous communities across the country to promote the rational and efficient use of energy, reaching 205,793 people (MPPEE, 2013).

In this research assessment, conducted over a four-year period (2013–2017), diesel genset projects' performance is analyzed in terms of energy production, equipment reliability and historical record of failures. In addition, technical visits, surveys and interviews with operators and beneficiaries are carried out. Results show the benefits of the support to national grid extension strategy (2) in terms of cost and fuel consumption. The support to distributed generation projects (3) mainly improves the supply quality of previously electrified houses. Finally, the off-grid strategy (1) can be an appropriate solution for particularly remote locations. The results of this investigation can be extrapolated to other developing countries in Latin America, sub-Saharan Africa and Southeast Asia, with similar characteristics than the projects studied in Venezuela (Palit and Bandyopadhyay, 2016).

The remainder of the paper is organized as follows. In Section 2, the 3 project strategies, their application to Venezuela and the data gathering methods used for the case studies are provided. The evaluation of the 3 strategies, based on the case studies, is described in Section 3. In Section 4, the results from the comparison are discussed in terms of the lifetime, cost and fuel consumption efficiency, identifying key aspects to be included in future project designs. Finally, the main conclusions are summarized in Section 5.

## 2. Project strategies and evaluation methods

In this section, first, the 3 diesel-based strategies are described, detailing the general design guidelines (Section 2.1). Then, the implementation of each option in Venezuela is presented, selecting real case studies for the analysis (Section 2.2). Finally, the data gathering methods (databases, surveys and interviews) used for the comparative evaluation are presented (Section 2.3).

### 2.1. Project strategies

This research focuses on the study of different strategies to implement rural electrification projects based on diesel-gensets. These projects are included in the DG category, which is defined as a generation capacity of up to 50 MW supplying a local load, under an off-grid or grid-connected scheme (Jain et al., 2017). In this work, diesel engines are the prime drivers of electrical generators in small power plants that can be connected at any point of the distribution network (Ackermann et al., 2001). The 3 common diesel-based strategies for rural electrification projects are:

(1) ***Off-grid*** (Fig. 1-a): diesel-gensets are used for the electrification of isolated rural communities not connected to the distribution grid.
(2) ***Support to national grid extension*** (Fig. 1-b): diesel-gensets are used to support the distribution grid in remote areas, in order to improve the voltage profile and service quality in previously electrified locations, while extending the grid towards the non-electrified dispersed population.
(3) ***Support to distributed generation*** (Fig. 1-c): diesel-gensets are used to support existing distributed generation power plants installed in areas of low population density, in order to improve the power quality and extend the grid towards non-electrified locations.

As observed, the first strategy uses an off-grid scheme, while the other two utilize a grid-connected configuration. In the three cases, the diesel generators allow up to two units to be under maintenance (N-2), at the same time, without causing interruptions in the electricity supply (Casado and Villaroel, 2013). Power transformers (Fig. 1) supply a bus bar where one or several medium voltage distribution lines are connected. In the grid-connected projects (Fig. 1-b and -c), new transformers are parallel to previous ones; and the distribution lines can supply electricity both to new and existing connections. Specifically, in Fig. 1-c, the new power transformers are placed parallel to some previous ones, since the generators are placed as a support for certain distribution grids. Finally, under the three schemes, downstream from the transformers, the MV distribution lines feed smaller MV/LV transformers from which end-users are finally supplied.

### 2.2. Selection of case studies

Since 2008, diesel-based electrification projects have been used in Venezuela for rural electrification within the program *"Revolución Energética"* ("Energy Revolution"), promoted by the national