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

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Abstract
From 2000 to 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.
Keywords: distributed generation, diesel generation sets, rural electrification, developing countries.

1. Introduction

Between 2000 and 2016 the number of people without access to electricity fell from 1,700 to 1,100 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, 1,310 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 (US EPA, n.d.). 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 (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, 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*** (Figure 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*** (Figure 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*** (Figure 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 (Figure 1) supply a bus bar where one or several medium voltage distribution lines are connected. In the grid-connected projects (Figures 1-b and 1-c), new transformers are parallel to previous ones; and the distribution lines can supply electricity both to new and existing connections. Specifically, in Figure 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 government (López-González et al., 2017a). The program focuses not only on new connections to the electricity service, but also on improving the voltage profile in previously electrified settlements with more than 40 houses and located more than 10 km from the distribution network, either as off-grid or grid-connected schemes. Concerning off-grid projects (1), the program has developed 8 projects where 34 diesel-genset units were installed with a total capacity of 45.5 MW (MPPEE, 2013). In terms of the support to national grid extension (2) and the support to distributed generation (3) strategies, 82 projects have been developed using 1,038 diesel-gensets and a total installed capacity of 1,145.1 MW (MPPEE, 2013). In order to carry out the evaluation of the three project strategies, 7 case studies from Northwestern Venezuela (states of Zulia and Falcón) are analyzed (Figure 2): 2 off-grid (Zapara Island and Cojoro), 3 support to national grid extension (Quisiro, San Carlos and Cuatro Esquinas) and 2 support to distributed generation (Coro and Dabajuro). The selection of the case studies analyzed in this paper is based on different aspects such as climate conditions (Rubel and Kottek, 2010), aiming to represent a wide range of locations in developing countries, particularly Africa and Southeast Asia.

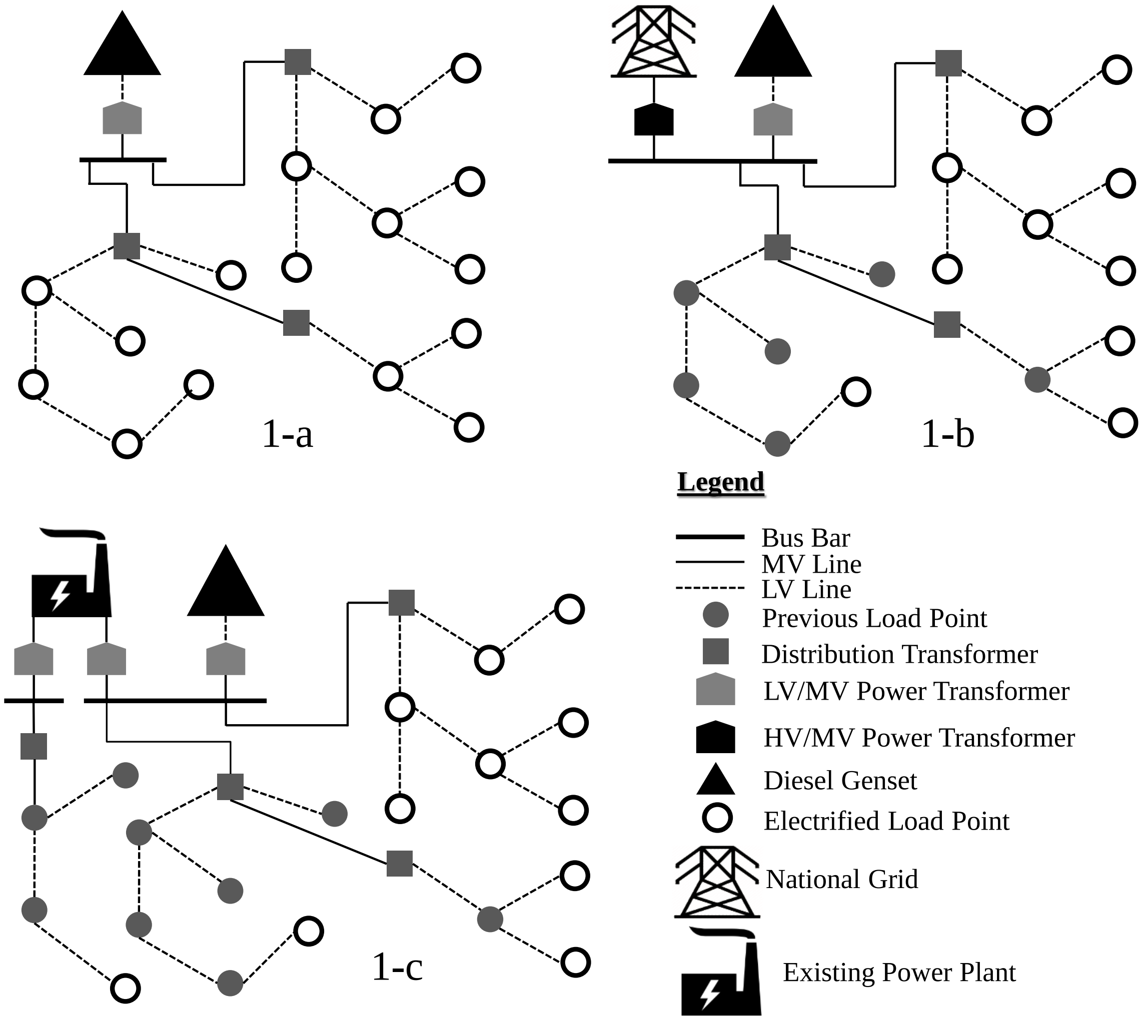

Figure 1. General scheme for the three project strategies: off-grid (1-a); support to national grid extension (1-b); and support to distributed generation (1-c) support to distributed generation

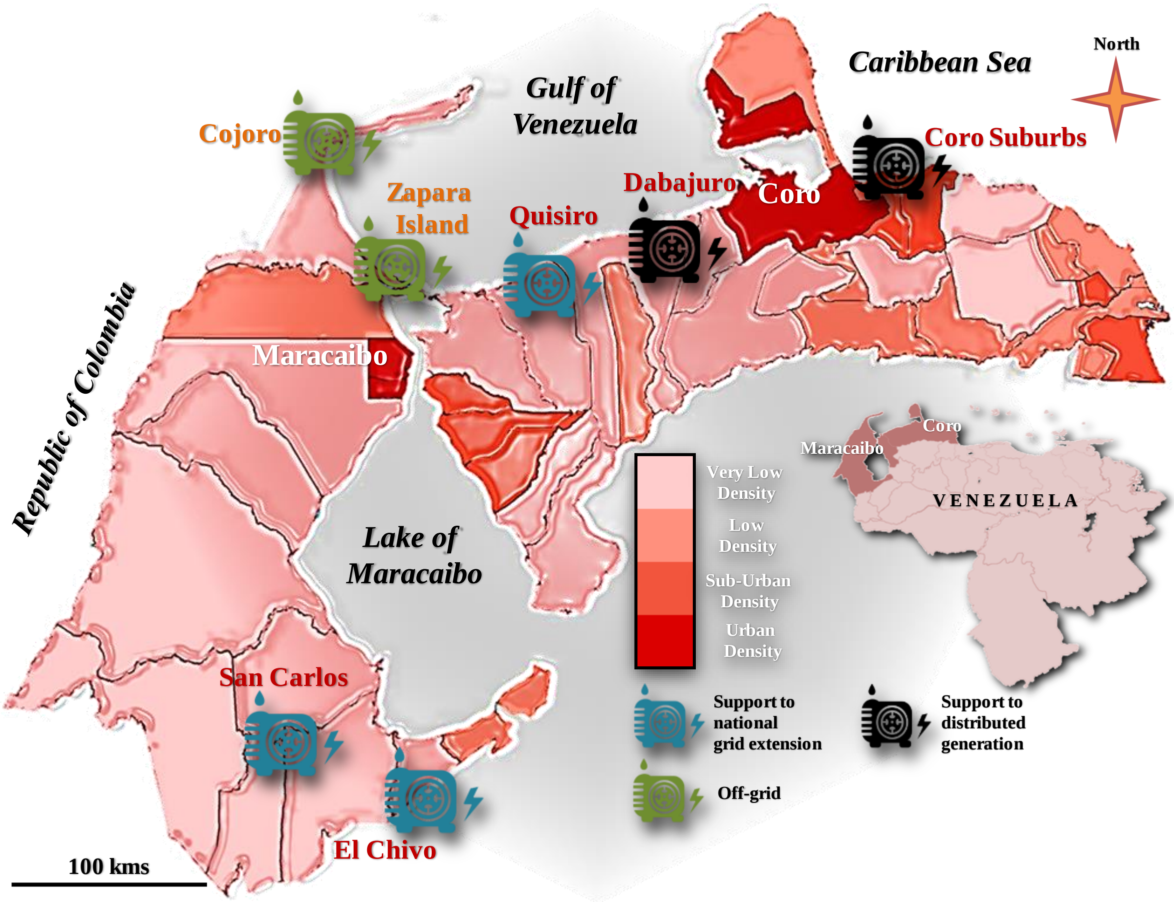

Figure 2. Location of the case studies and population density in Northwestern Venezuela

2.3. Data gathering methods

The evaluation of a project starts with an analysis of the historical record of energy production, fuel consumption, technical operator annotations, failure reports, etc. Using this information, the causes of the most common failures are identified (management, maintenance, etc.). In addition, as an estimator of the capacity factor, the generation data is used together with the operating hours of each unit to determine the average level of production over capacity. Moreover, from the fuel consumption data, the specific consumption per generated energy (l/kWh) is obtained, indicating the thermal efficiency.

Next, the technical visits to the communities are carried out. This process starts with an inspection visit to determine information such as: operational parameters of the diesel-genset units (temperature, physical condition, etc.), location of polluting waste and the storage conditions, fuel management procedures, etc. Regarding evaluation of the availability of the diesel units, the standard IEEE 762 process is used (IEEE Power Engineering Society, 2007). The availability factor (AF) is calculated as the ratio between the available and the installed capacity, considering the forced outage rate and the capacity limitation (usually thermal or vibrational). In case of frequent problems in supply quality, the voltage is measured at critical points (near to the generator and at the furthest point from it, for example). Finally, the distribution grid is examined in order to find possible hot spots (Ma et al., 2010), corrosion, illegal connections, etc.

During the technical visits, semi-structured surveys of beneficiaries are also carried out. First, the socioeconomic characteristics of the families are analyzed; that is, the age, educational level, productive activities, incomes, etc. Second, the perceived quality and opinions of the electricity service are examined from the end-users' perspective.

3. Description and evaluation of the project strategies

In this section, the 3 project strategies are described and evaluated: off-grid (Section 3.1), support to national grid extension (Section 3.2) and support to distributed generation (Section 3.3). Table 1 summarizes the technical characteristics of the visited case studies for each strategy.

Table 1. Technical characteristics of the case studies visited

Project strategy	Case study	Generation units	Unit generation capacity (kW)	Total capacity (MW)	New electrified houses
Off-grid	Zapara Island	4	400	1.6	120
	Cojoro	6	400	2.4	150
Support to national grid extension	Quisiro	4	1500	6	400
	San Carlos	8	1500	12	870
	Cuatro Esquinas	18	360	6.5	1000
Support to distributed generation	Coro	8	1800	14.4	800
	Dabajuro	6	1800	10.8	470

3.1. Off-grid

Before the implementation of the "Energy Revolution" program the electricity service on Zapara Island was based on diesel generators, which only supplied 72% of the houses for 4 h/day. In Cojoro, only 4.1% of the houses had access to electricity from diesel domestic plants. In both communities, the national grid extension is not feasible, so off-grid rural electrification projects were implemented. The electricity tariff is collected equitably and periodically (and occasionally, in the case of major breakdowns). However, differences in consumption can be observed given the different income levels of the families. The communal council of each community, together with community operators (employees of the Electrical Service Company, ESC, and assigned to each project in 24 h shifts), are responsible for the operation, maintenance and management tasks.

Zapara Island is located 9.3 km from San Carlos Island, which is the closest electrified village (via a submarine cable from the mainland) (Instituto Nacional de Estadística, 2014). The electrification project in Zapara Island includes two settlements connected by a 900 m 13.8 kV line, and a total of 120 houses. The diesel reserve implies a 25-day autonomy. However, there have been failures in the supply due to tide and climate conditions, with cuts of up to two weeks. In this regard, shortages in the supply of air and oil filters, lubricating oil and batteries have also been reported. The 4 diesel units operate equally, between 6 and 9 h/day each. The average specific fuel consumption is high (0.294 l/kWh), since the demand is still very low and the diesel generators do not always operate close to their nominal capacity (maximum efficiency). The electricity supply enables some houses to have air conditioning equipment and more than one refrigerator. However, some users report that light bulbs and other electrical devices are frequently damaged due to voltage variations. The proximity to the sea and the scarcity of rainfall, typical of the desert climate (Rubel and Kottek, 2010), have caused corrosion in the electricity lines and distribution posts as well as in the main electrical substation. Hence, after 6 years of operation, only 1 out of the 4 generators remains operative (AF of 25%), which causes time restrictions in the electricity supply. In addition, given the remote location of the island, failures in the diesel-gensets can take up to 3 months to be repaired, while repairs to the distribution network take from 1 to 2 days to be carried out.

Cojoro is a Wayuu indigenous community located 41 km from Paraguaipoa, the nearest electrified settlement (Instituto Nacional de Estadística, 2014). Since the diesel-gensets were installed (Figure 3), Cojoro has been growing and the number of new connections has increased (some of them unauthorized) to 150 houses. The electrification project has fuel autonomy for about 30 days, with the trucks taking around 3 travelling hours to restock supplies. The system includes 6 units operating equally; between 4 and 6 h/day each. The average specific fuel consumption is high (0.283 l/kWh), since the demand is still very low and the diesel generators do not always operate close to their nominal capacity. Some houses have air conditioning and more than one refrigerator, but the voltage fluctuations cause the lifetime of the light bulbs and other devices to be reduced. Indeed, voltage measures indicate failures in the distribution network regulation, caused by the characteristics of the desert climate (Rubel and Kottek, 2010) and the existence of hot spots (Ma et al., 2010). In addition, there has been a significant growth in the grid connections (around 30 houses) without the required regulatory measures. Consequently, after the first 3 years of operation, the AF reached 67%, falling to 33% after 6 years. Despite the difficulties presented, monitoring of the systems by the communal council has meant that the plant remains operational. Finally, it should also be noted that there have been issues in the supply of air and oil filters, as well as lubricating oil and electrical batteries for combustion engines, caused by the remoteness of the community.

Figure 3. Diesel-gensets in Cojoro (generators and power transformers)

3.2. Support to national grid extension

As electricity demand in rural areas has grown, the distribution grid has been increasingly overloaded, causing frequent voltage drops and interruptions. In this regard, the grid extension towards non-electrified locations becomes progressively more difficult. In these rural areas of Venezuela, around 65-85% of the settlements have less than 20 houses, with 30-50% being non-electrified (Instituto Nacional de Estadística(INE), 2003). In addition, nearly 10% of the population is extremely dispersed. Therefore, in order to achieve grid extension, diesel-gensets are installed at the end of the existing distribution network to improve the voltage profile. In this regard, the electrification projects at the communities of Quisiro, San Carlos and Cuatro Esquinas aim to support the distribution grid during peak demand periods, while providing enough capacity to include new connections without compromising previously electrified locations. The houses in these communities have consumption meters, as in other locations supplied via the national grid. The operation of the generation units and the preventive maintenance is carried out by technicians working in weekly shifts, during which they stay in the nearest town. Technicians in charge of major maintenance activities are based in the most important regional headquarters of the ESC; in the case of the studied projects, the city of Maracaibo.

The project at Quisiro village supports the existing grid, 24.6 km from the distribution substation, and 400 houses have been added to the distribution network. The fuel storage tank has autonomy for 30 days under typical consumption patterns, the trucks taking about 1.3 travelling hours for resupply. The system operates for about 10.5 h/day, each unit working at 83.6% of the nominal capacity. The average specific fuel consumption is 0.269 l/kWh, which is lower than in the off-grid projects. During the first 3 years of operation, the AF fell to 25% and remained so until the sixth year. In addition, given the operational complexity of this project, failures in the fuel pumps produce thermal limitations, thereby reducing the maximum generation capacity. However, thanks to the project oversize, it can still withstand the load during the required hours.

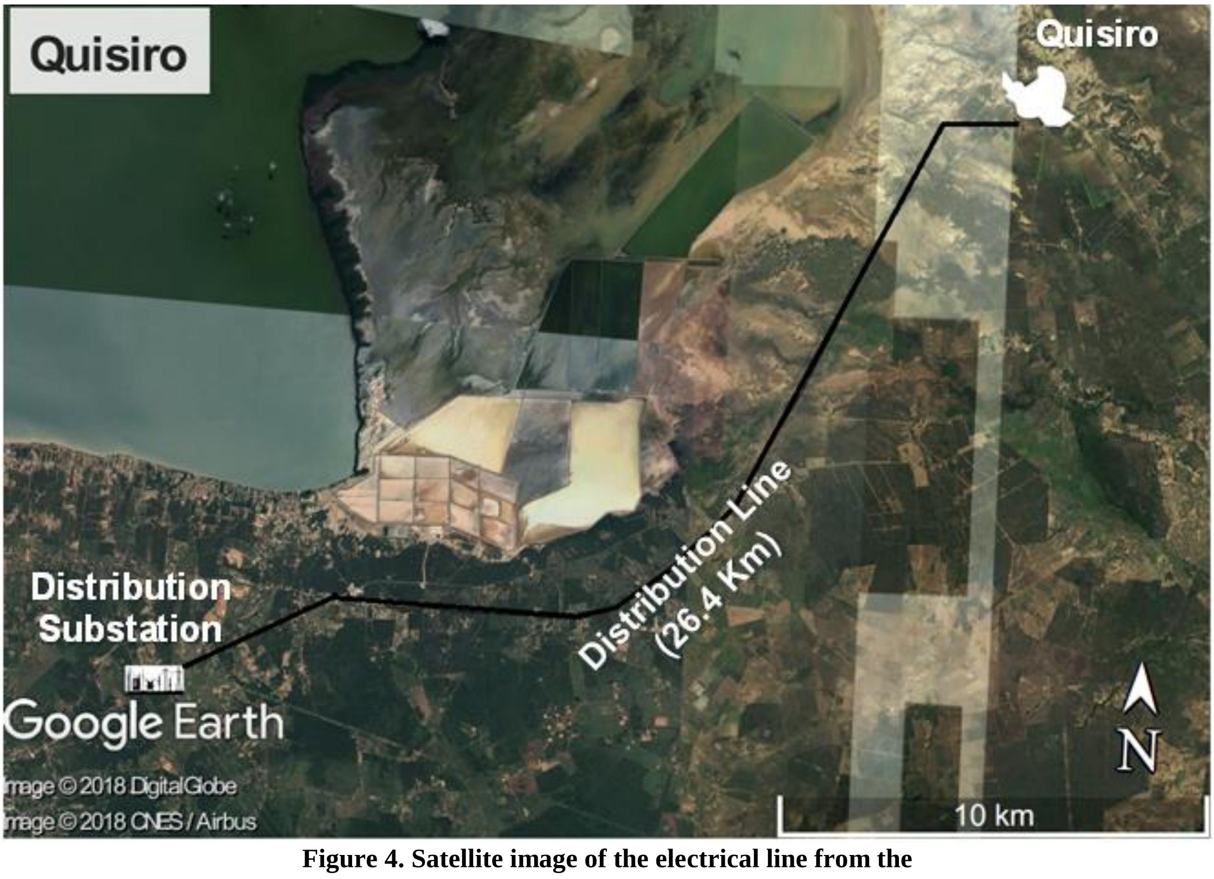

Figure 4. Satellite image of the electrical line from the distribution substation to the rural diesel power plant in Quisiro

The electrification project at the community of San Carlos has led to a 27% increase in houses, with the subsequent demand growth, during the first 6 years of operation (Instituto Nacional de Estadística(INE), 2013). The project supports the existing grid at peak demand hours and supplies 870 new houses included in the distribution network. The fuel storage tank has autonomy for 80 days, the trucks taking around 6 travelling hours for resupply. The system operates around 12 h/day, each unit working at 93.0% of the nominal capacity. The average specific fuel consumption is 0.260 l/kWh. Thanks to the proximity to an urban population center, the maintenance conditions are better than in other projects included in this strategy. However, during the first 3 years of operation the AF fell to 75% and after 6 years to 50%. In this case, the operation regime has been in accordance with the initial design and the unavailability of some generators is due to them reaching the limits of their useful lifetime under such conditions.

The project at Cuatro Esquinas supports the existing grid and supplies electricity to 1,000 previously non-electrified houses. The fuel storage tank has autonomy for 25 days, the trucks taking 7 travelling hours for resupply. The system operates, on average, 8 h/day, each unit working at 39.1% of the nominal capacity, mainly due to operational limitations caused by high engine temperatures. The average specific fuel consumption is high (0.282 l/kWh). There are 5 units out of service and some of the components have been removed to be used as spare parts in the generators with minor damages. During the first 3 years, the AF of the project dropped to 65%. Subsequently, due to the remoteness of the community from the maintenance centers, the number of generation units out of service rose to 16 after 6 years, which means an AF of 11%. The replacement frequency of consumables is high in Cuatro Esquinas, so waste from burnt lubricant (Figure 5-a), air and oil filters (Figure 5-b) and electric batteries (Figure 5-c) can be observed in the surroundings. As this is an agricultural area with highly fertile land, thanks to the tropical climate (Rubel and Kottek, 2010), such polluting chemical waste could be detrimental for the productivity of neighboring farms.

Figure 5. Cuatro Esquinas: (a) lube oil drums, filled with used oil, (b) electric batteries of reciprocating engines, and (c) used air filters and lubricating oil, stored and waiting for removal

3.3. Support to distributed generation

In DG plants located in areas far from the national grid, most of the failures are caused by the growth of rural electricity demand, particularly during peak hours, such as the diesel distributed generation power plants installed in the communities of Coro and Dabajuro. At these locations, from 72% to 82% of the settlements have less than 20 houses, with only 20% being electrified. In addition, between 3% and 21% of the population is completely dispersed (Fundelec, 2012). Therefore, the grid extension must be achieved by means of projects aiming to improve the voltage profile of previously electrified locations while enabling the inclusion of new non-electrified houses, avoiding voltage drops and electricity interruptions. Both in Coro and Dabajuro, the houses have electricity consumption meters. The operation of the diesel-gensets and the preventive maintenance is carried out by the technicians of the existing DG plants, before the installation of the support diesel generators. The technicians in charge of major maintenance are located in the most important regional headquarters of the ESC.

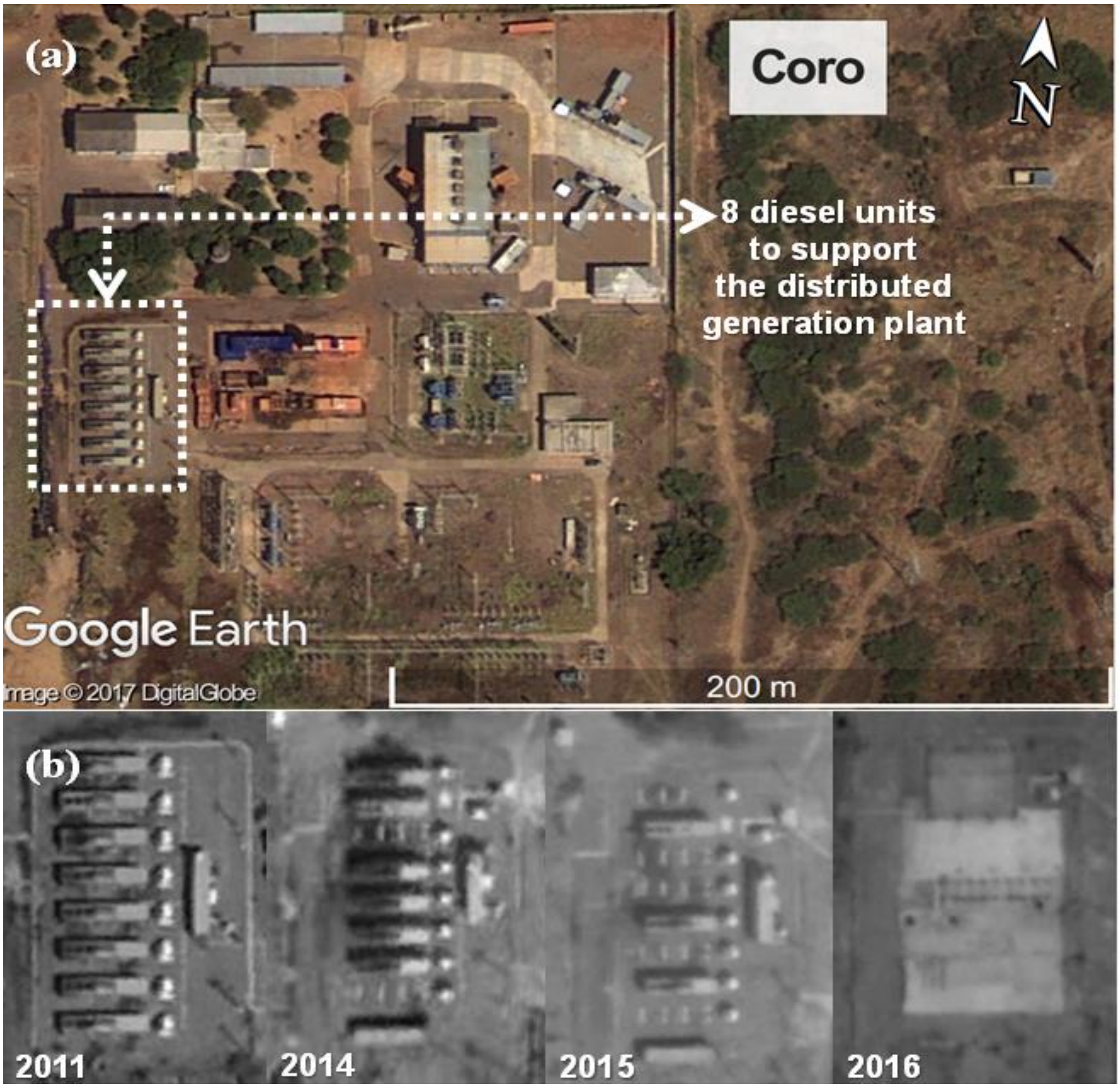

Figure 6. (a) Satellite image of the support diesel generators located in the Coro distributed generation site during its operation in 2011 and (b) available units in 2011, 2014, 2015 and 2016

The electrification project set up in the community of Coro consists of 8 diesel-genset units to support an existing distributed generation power plant and previously electrified houses during peak demand hours (Figure 6-a), while supplying electricity to 800 new connections. The new and existing generators are connected to the same distribution substation (Figure 6-a). The fuel storage tank is shared with the existing one. The system operates about 14 h/day, each unit working at nominal capacity between 6 and 9 h/day. The average specific fuel consumption is low (0.260 l/kWh). There is 1 unit out of service due to a failure in the lubrication system that caused permanent engine damage. In this case, the generators have problems in terms of the fuel transfer conditions in the centrifugal pumps. In addition, the high operating temperatures, due to the desert climate (Rubel and Kottek, 2010), limit the generation capacity. Therefore, in 2014 two units were completely uninstalled, another five in 2015 and, in 2016, the ESC removed all the units due to the high costs of operation and maintenance (Figure 6-b). The project was replaced by aero-derivative light turbines.

The project in Dabajuro community supports a previously existing DG plant at peak hours as well as 470 newly electrified houses. The fuel storage tank is shared with the existing one. The system operates almost 14 h/day, with each unit working at 70.6% of the nominal capacity between 6 and 9 h/day, both as support to the distribution network and in isolated mode for long interruptions. The average specific fuel consumption is 0.266 l/kWh. There is 1 unit out of service due to an operating system in which the required maintenance was not performed. In this regard, the diesel unit was permanently damaged, and a year later another unit also failed permanently. In mid-2016, only 4 units remained operational, although with thermal operating limitations due to the high temperatures of the desert climate (Rubel and Kottek, 2010), which implies an AF of 40.1%. In this same year, the ESC decided to gradually replace the engines by light turbines that, under a permanent operating mode, have a higher stability (Figure 7).

Figure 7. Light turbines for the replacement of generators with reciprocating diesel engines in the distributed generation site of Dabajuro

4. Project strategies comparison and discussion

The discussion of results first focuses on an analysis of the lifetime of the 3 project strategies and the key issues influencing it (Section 4.1). Next, the strategies are compared in terms of the investment cost and fuel consumption (Section 4.2). Table 2 shows a comparison of indicators considered in the discussion, calculated as a mean of the case studies presented in Section 3. This table enables the investment efficiency to be compared, according to the installed capacity for the electrification of a given number of houses, and the influence of the operating regime on the fuel consumption in each strategy.

4.1. Lifetime analysis

Failure records and the trends in the AF show that motors for electricity generation require frequent operation and maintenance activities, as well as a stock of high rotation consumables, such as fuel or air and oil filters. Considering the remoteness of the projects studied, significantly long repair times can be expected, with the specialized maintenance technicians and the warehouses for consumables being several hours away. In all the cases analyzed, failures have been observed in the supply of air and oil filters, as well as the lubricating oil and electrical batteries for the combustion engines. The high replacement frequency needed for these consumables has caused drums of used lubricating oil, as well as other consumables, to be stored on the site.

Table 2. Comparison of project strategies according to different indicators

Connection	Strategy	Weighted availability factor (WAF, %)		Daily working hours	Fuel consumption (l/kWh)	Investment efficiency (houses/MW)
		3 years of operation	6 years of operation			
Isolated	Off-grid	80.0	29.8	24	0.289	68
Grid-connected	Support to national grid extension	60.1	45.8	8-12	0.268	93
	Support to distributed generation	85.7	17.2	14	0.262	50

During the technical visits, difficulties caused by the long repair times were observed, such as the low weighted availability factor (WAF) in all the case studies during the first operative years. After 6 years, the WAF for the national grid extension is 45.8% and for the support to distributed generation projects 17.2% (Table 2). The off-grid projects also have significant capacity losses, despite having permanent operators at their location. The WAF in these projects, after 6 years, is 29.8% (Table 2). Consequently, the lifetime of the studied projects should not be considered beyond 9-10 years for applications in developing countries, where access to rural areas is not easy and the maintenance management is not always effective. This value has been extrapolated from Table 2, according to the average WAF of the three strategies. In this regard, measures seeking to carry out maintenance activities as carefully as possible are the key to extending the projects' lifetime.

4.2. Cost and consumption comparison

In off-grid projects, the fuel consumption per produced energy (0.289 l/kWh), is higher than in the support to national grid extension (0.268 l/kWh) and the support to distributed generation (0.262 l/kWh) projects (Table 2). However, it must be noted that the fuel consumption in the analyzed case studies is lower than the one obtained by Díaz et al. (2010) in a five-year analysis made for similar gensets and operative conditions in off-grid diesel projects in northern Argentina: between 0.3 and 0.35 l/kWh. This is due to northern Argentina gensets usually operate at less than a 25% of their capacity, which decreases their efficiency. Thus, grid-connected projects have an average 9.3% lower fuel consumption (l/kWh) than off-grid projects; consequently, they have a lower average emission factor ($kgCO_2/kWh$). This is due to the fact that off-grid diesel-gensets operate 24 h/day, whatever the demand, so engines mostly work far from their nominal power. Moreover, grid-connected projects only work part-time (from 8 to 14 h/day) during peak demand hours, so they can work closer to their nominal capacity and high efficiency.

From the analysis of the case studies, the support to national grid extension scheme supplies enough electricity to reach a larger number of beneficiaries with a lower generation capacity (lower investment cost), making it the most effective option for rural electrification, where possible. In this sense, 93 houses are electrified per installed MW, while for the off-grid and support to distributed generation projects, the value is 68 and 50, respectively (Table 2). Indeed, where support to distributed generation projects are implemented, the main benefit is to maintain adequate voltage profiles for previously electrified users, rather than extending the grid towards non-electrified houses. Finally, comparing the support to national grid extension and the off-grid projects, higher investment costs are required in the second option. Therefore, off-grid diesel generators are mainly suitable in remote locations where the grid extension is not economically profitable.

This research achieves a wide comprehension of the studied diesel genset strategies. Some authors, such as Mainali and Silveira (2013), have analyzed diesel genset projects as an off-grid electrification technology, but not considering them as a support for grid extension or distributed generation, as in this paper. In doing so, they compared them with RET-based off-grid strategies, obtaining favorable results. However, among the different strategies when diesel genset electrification is feasible, no conclusions have been achieved. On the other hand, Slought (2015), analyzed small-scale diesel gensets in Brazil for domestic use, while the proposed research assesses a national program where large-scale diesel gensets promote the replacement of small and inefficient domestic diesel generators (Cojoro case study), which has not been done before in the literature.

5. Conclusion

The diesel technology is expected to be significantly used in the coming years to achieve universal access to electricity in rural areas of Venezuela and other developing countries. In this context, the objective of this research is to identify which strategy is the most appropriate for extending electrification to non-electrified locations, reducing costs while maximizing fuel efficiency. In particular, three strategies are analyzed: off-grid, support to national grid extension and support to distributed generation. The comparison is based on case studies implemented in Venezuela as part of the "Energy Revolution" program. More specifically, real generation data is examined, as well as the operational data for several years, interviews and surveys of technical operators and beneficiaries.

Results show that the lifetime of the three project strategies is conditioned by a set of factors that depend on geographical, climatic and logistical conditions that are more common than in other technologies or electrification strategies, such as renewable energy. In this sense, diesel projects are very vulnerable, with high maintenance and operation costs, and their lifetime does not exceed 10 years. In terms of fuel consumption, grid-connected projects are the most efficient as they mainly work at peak demand hours, very close to their nominal capacity. Among the grid-connected projects, the support to national grid extension can supply a larger number of houses per installed capacity; i.e. they are the most efficient in terms of investment cost. On the other hand, in the support to distributed generation, main beneficiaries are previously electrified users, so such projects must be used preferably as a voltage profile improvement strategy for rural areas, rather than a grid extension option. Finally, off-grid projects have higher investment costs than the support to national grid extension but are a suitable alternative where the grid extension is not feasible.

The above-mentioned results can assist rural electrification promoters to effectively determine the most appropriate strategy, according to the financial availability and the community characteristics (local resources, fuel consumption, etc.), while seeking to mitigate greenhouse gas emissions through optimal operational schedules.

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References

Ackermann, T., Andersson, G., Söder, L., 2001. Distributed generation: A definition. Electr. Power Syst. Res. 57, 195–204. doi:10.1016/S0378-7796(01)00101-8

Alliance for Rural Electrification (ARE), 2014. Mini-Grids for Rural Electrification, Alliance for Rural Electrification. Brussels.

APP, 2017. Lights, Power, Action: Electrifying Africa.

Banal-Estañol, A., Calzada, J., Jordana, J., 2017. How to achieve full electrification: Lessons from Latin America. Energy Policy 108, 55–69. doi:10.1016/j.enpol.2017.05.036

Bloomberg, 2017. 3Q 2017 Frontier Power Market Outlook. NY.

Bureau, I.D., Growth, E., 2004. Increasing Energy Access in Developing Countries: The Role of Distributed Generation.

Agriculture.
Carley, S., 2009. Distributed generation: An empirical analysis of primary motivators. Energy Policy 37, 1648–1659. doi:10.1016/j.enpol.2009.01.003
Casado, O., Villaroel, G., 2013. Grupos electrógenos y centrales eléctricas de generación distribuida, 2nd ed. Createspace Independent Publishing Platform, Caracas.
Cid-Serrano, L., Ramírez, S.M., Alfaro, E.J., Enfield, D.B., 2015. Analysis of the Latin American west coast rainfall predictability using an enso index. Atmosfera 28, 191–203. doi:10.20937/ATM.2015.28.03.04
Díaz, P., Arias, C.A., Peña, R., Sandoval, D., 2010. FAR from the grid : A rural electrification field study 35, 2829–2834. doi:10.1016/j.renene.2010.05.005
Fundelec, 2012. Programa "Sembrando Luz." Caracas.
Fuso Nerini, F., Howells, M., Bazilian, M., Gomez, M.F., 2014. Rural electrification options in the Brazilian Amazon. A multi-criteria analysis. Energy Sustain. Dev. 20, 36–48. doi:10.1016/j.esd.2014.02.005
Haghighat, A., Alberto, S., Escandon, A., Naja, B., Shirazi, A., Rinaldi, F., 2016. Techno-economic feasibility of photovoltaic , wind , diesel and hybrid electri fi cation systems for off-grid rural electri fi cation in Colombia. Renew. Energy J. 97, 293–305. doi:10.1016/j.renene.2016.05.086
IEA, 2017. Energy Access Outlook 2017: From poverty to prosperity. Paris.
IEEE Power Engineering Society, 2007. Standard Definitions for Use in Reporting Electric Generating Unit Reliability, Availability, and Productivity, IEEE Std 762™-2006 (Revision of IEEE Std 762-1987). doi:10.1109/IEEESTD.2007.335902
Instituto Nacional de Estadística(INE), 2013. Censo 2011 Redatam-Venezuela [WWW Document]. Censo Nac. Población y Vivienda 2011. URL http://www.redatam.ine.gob.ve/Censo2011/index.html (accessed 11.21.17).
Instituto Nacional de Estadística(INE), 2003. Censo 2001 Retadam-Venezuela [WWW Document]. Censo Población y Vivienda 2001. URL http://www.ine.gov.ve/index.php?option=com_content&view=category&id=95&Itemid# (accessed 11.21.17).
Instituto Nacional de Estadística, 2014. XIV Censo Poblacional de Población y Vivienda. Resultados por Entidad Federal y Municipio del Estado Zulia. Caracas.
Jain, S., Kalambe, S., Agnihotri, G., Mishra, A., 2017. Distributed generation deployment: State-of-the-art of distribution system planning in sustainable era. Renew. Sustain. Energy Rev. 77, 363–385. doi:10.1016/j.rser.2017.04.024
Khennas, S., Barnett, A., 2000. Micro-hydro power: an option for socio-economic development, in: Sayingh, A. (Ed.), World Renewable Energy Congress If"1 (WREC2000). Elsevier Ltd, Rugby, UK, pp. 1511–1517.
Khodayar, M.E., 2017. Rural electri fi cation and expansion planning of o ff -grid microgrids. Electr. J. 30, 68–74. doi:10.1016/j.tej.2017.04.004
Kyte, R., 2017. Learning from the success stories. Sustainable energy for all is possible through sharing good examples. World Energy Focus 3–4.
Lahimer, A.A., Alghoul, M.A., Yousif, F., Razykov, T.M., Amin, N., Sopian, K., 2013. Research and development aspects on decentralized electrification options for rural household. Renew. Sustain. Energy Rev. doi:10.1016/j.rser.2013.03.057
López-González, A., Domenech, B., Ferrer-Martí, L., 2017a. Renta petrolera y electrificación en Venezuela : Análisis histórico y transición hacia la sostenibilidad. Cuad. Latinoam. 51, 1–24.
López-González, A., Domenech, B., Gómez-Hernández, D., Ferrer-Martí, L., 2017b. Renewable microgrid projects for autonomous small-scale electrification in Andean countries. Renew. Sustain. Energy Rev. 79, 1255–1265. doi:10.1016/j.rser.2017.05.203
Ma, J., Tehranipoor, M., Sinanoglu, O., Almukhaizim, S., 2010. Identification of IR-drop hot-spots in defective power distribution network using TDF ATPG, in: IDT'10 - 2010 5th International Design and Test Workshop, Proceedings. pp. 122–127. doi:10.1109/IDT.2010.5724422
Mainali, B., Silveira, S., 2013. Alternative pathways for providing access to electricity in developing countries. Renew. Energy 57. doi:10.1016/j.renene.2013.01.057
MPPEE, 2013. Anuario estadístico 2013: Sector Eléctrico Venezolano. doi:201108DC35
Narula, K., Nagai, Y., Pachauri, S., 2012. The role of Decentralized Distributed Generation in achieving universal rural electrification in South Asia by 2030. Energy Policy 47, 345–357. doi:10.1016/j.enpol.2012.04.075
Palit, D., Bandyopadhyay, K.R., 2016. Rural electricity access in South Asia: Is grid extension the remedy? A critical review. Renew. Sustain. Energy Rev. 60, 1505–1515. doi:10.1016/j.rser.2016.03.034
Paliwal, P., Patidar, N.P., Nema, R.K., 2014. Planning of grid integrated distributed generators: A review of technology, objectives and techniques. Renew. Sustain. Energy Rev. 40, 557–570. doi:10.1016/j.rser.2014.07.200
Rubel, F., Kottek, M., 2010. Observed and projected climate shifts 1901-2100 depicted by world maps of the Köppen-Geiger climate classification. Meteorol. Zeitschrift 19, 135–141. doi:10.1127/0941-2948/2010/0430
Slough, T., Urpelainen, J., Yang, J., 2015. Light for all? Evaluating Brazil's rural electrification progress, 2000-2010. Energy Policy 86, 315–327. doi:10.1016/j.enpol.2015.07.001
Strachan, N., Farrell, A., 2006. Emissions from distributed vs. centralized generation: The importance of system performance. Energy Policy 34, 2677–2689. doi:10.1016/j.enpol.2005.03.015
Suárez, J.A., Beatón, P.A., Escalona, R.F., Montero, O.P., 2012. Energy, environment and development in Cuba. Renew. Sustain. Energy Rev. 16, 2724–2731. doi:10.1016/j.rser.2012.02.023
Szabó, S., Bódis, K., Huld, T., Moner-Girona, M., 2011. Energy solutions in rural Africa: mapping electrification costs of distributed solar and diesel generation versus grid extension. Environ. Res. Lett. 6, 034002. doi:10.1088/1748-9326/6/3/034002
Terrapon-Pfaff, J., Dienst, C., König, J., Ortiz, W., 2014. A cross-sectional review: Impacts and sustainability of small-scale renewable energy projects in developing countries. Renew. Sustain. Energy Rev. 40, 1–10.

doi:10.1016/j.rser.2014.07.161
United Nations, 2015. Transforming our world: The 2030 agenda for sustainable development, A/RES/70/1. doi:10.1007/s13398-014-0173-7.2
UPME, 2014. Plan indicativo de expansión de cobertura de energía eléctrica 2013-2017. Bogotá. doi:10.1017/CBO9781107415324.004
US EPA, O., n.d. Distributed Generation of Electricity and its Environmental Impacts.
Yuan, G., 2015. Rural Electrification Goes Local: Recent innovations in renewable generation, energy efficiency, and grid modernization. IEEE Electrif. Mag. 16–24.