Abstract:

Colombia, like many other low and middle-income countries, faces an electricity access deficit. Even where access is available, many off-grid communities are only provided with a few hours of service, typically using diesel, which is expensive and polluting. Using a system dynamics model, this paper investigates how a sustainable and durable electricity supply can be provided in off-grid communities in Colombia. The scenarios examined draw on two government funds that have been established to: deliver the infrastructure and provide subsidies for electricity supply. The results demonstrate that a transition from diesel to renewables is not only possible but also economically viable and desirable. The simulations also show that in order to make the best use of limited government funding for electrification, the transition from diesel to renewables should begin as soon as possible and be accompanied by a zero-diesel policy by 2040. Furthermore, the model highlights that electricity systems should be designed to enable gradual growth in demand – driven by socio-economic development and productive uses. Given the imperative to provide a sustainable and durable electricity supply to off-grid communities, this paper provides insights into how this can be achieved while delivering clear benefits for users, utilities and the government.

Keywords: Off-grid electrification, electricity supply, sustainability, system dynamics, Colombia.

1. Introduction

Electricity is one of the key drivers for the sustainable development of low-income communities (Dyner et al., 2005; Kanagawa and Nakata, 2008; Rahman et al., 2013; Silva and Nakata, 2009; Tomei et al., 2020). And yet, in 2020, an estimated 770 million people worldwide lacked access to electricity (IEA, 2021). The supply of electricity to off-grid communities has focused on diesel-powered microgrids, interconnections to the national grid and, to a lesser extent, mini-hydropower generators (Come Zebra et al., 2021; Terrado et al., 2008). However, this focus is changing; for example, in sub-Saharan Africa, electrification with renewable technologies is becoming more frequent (IRENA, 2021), while in countries such as Bolivia, solar hybridisation of diesel microgrids is making progress (Ortiz-Jara et al., 2020). In Colombia, diesel generators remain common, although due to the high cost of fuel, electricity is typically only supplied for a few hours per day (Garces et al., 2021).

As the price of renewable energy continues to fall, the use of such technologies for off-grid electrification is accelerating (IRENA, 2021, 2019, 2017a; Ortiz-Jara et al., 2020). Solar photovoltaic (PV) is one of the most popular options and offers advantages over other generation systems. It relies on solar radiation, which is abundant across different world regions, has low maintenance requirements, and capacity additions are simple and modular (Jimenez et al., 2014). Furthermore, falling prices, combined with the increased efficiency of end-use devices, have increased the affordability of solar and other renewable energy technologies (IRENA, 2020, 2019). Once it is (economically) viable to complement such systems with battery storage, it will be possible to envisage the development of 24-hour supply to currently (un)electrified communities – a process which will support socio-economic development worldwide.

While it is reported in the literature that access to electricity is strongly related to socio-economic development (Boliko and Ialnazov, 2019; Chaurey et al., 2004; Dyner et al., 2005; IRENA, 2017a; Kanagawa and Nakata, 2008; Krithika and Palit, 2013; Mandelli et al., 2016), low-income communities do not progress simply by having access to electricity infrastructures. Rather, policies to promote electrification should take a more holistic view that considers the opportunities that enhanced access can provide for productive activities, such as agriculture and cold storage, and other household and community uses, such as education, health and street lighting (IEA, 2017; Tomei et al., 2020).

Regarding access to electricity in Colombia, the country faces three challenges in the provision of sustainable energy for all: 1) the provision of electricity to those who currently lack access; 2) increasing the hours of electricity supply in smaller off-grid areas; and 3) increasing the affordability of electricity for consumers in off-grid areas. The policies designed to address these challenges are described below:

With respect to the first challenge, the Colombian government has promoted expansion through the Indicative Expansion Plan of Electric Power Coverage (PIEC). The PIEC 2019-2023 aims to deliver electricity to the 1.9 million people who currently lack access and considers the use of solar PV solutions, including stand-alone systems and hybrid microgrids (Garces et al., 2021; UPME, 2019). However, the PIEC is narrowly focused on the provision of infrastructure to communities without access to electricity; it is not concerned with enhancing existing provision, e.g. limited hours of service (UPME, 2019).

Concerning the second challenge, a large proportion of off-grid communities with access to electricity have only limited service. This is driven by two key factors: 1) electricity supply is largely provided through diesel generators (SSPD, 2021), and 2) Colombian regulation limits subsidies according to the number of users served per locality. For example, localities of Type 3 (51-150 users) and Type 4 (0-50 users) have a subsidized consumption of five and four hours per day respectively (MME, 2007). As a consequence of the regulatory limits on subsidies, this challenge is concentrated in smaller communities – those with less than 150 users which represent around 87.5% of off-grid communities in Colombia (Garces et al., 2021; SSPD, 2020). In September 2021, 89% of 1,636 villages in Colombia had less than seven hours of electricity per day (IPSE and CNM, 2021); the vast majority (91%) of these were Type 3 and 4 which have on average 4.95 and 4.04 hours of service respectively (SUI, 2019a).

Relating to the third challenge of affordability, the Colombian government has allocated funds to finance the provision of electricity service in off-grid areas – or *Zonas No Interconectadas* in Colombia (ZNI) (Garces et al., 2021). Two of the most important are the Financial Support Fund for the Energization of Non-Interconnected Zones (FAZNI) and the Solidarity Fund for Subsidies and Income Redistribution (FSSRI). While FAZNI supports the financing of new installed capacity, FSSRI supports the operation of off-grid electrification plants (Garces et al., 2021; SSPD, 2019). The FSSRI provides subsidies for electricity to low-income domestic users in both rural and urban areas (MME, 2020). In the ZNI, these subsidies are used to cover the difference between the tariff that users pay and the Unit Cost of Service Provision (CU), which comprises generation, distribution and commercialization costs (CREG, 2007). In 2020, the average tariff for the poorest users was 0.07[1] US$/kWh and CU was 0.40 US$/kWh (SSPD, 2021). This means that for the poorest users, the subsidy provided by the FSSRI covered slightly more than 80% of the average CU. The Ministry of Mines and Energy (MME) is responsible for determining the amount of the subsidy to be granted to companies that provide electricity to ZNI (MME, 2007). These companies are as diverse as the localities themselves; for example, the larger localities such as San Andres and Leticia have utility companies, while smaller localities generally have management boards, service cooperatives, user associations, and many others (CREG, 2020). These companies will be referred to as electricity service providers (ESP).

This research focuses on the second and third challenges outlined above and extends the work carried out in Garces et al. (2021), in which the authors' analysed Colombia's policy context by examining funds and strategies for renewable energy roll-out and the potential impacts on ZNI communities. This paper aims to assess the performance of different strategies that enhance sustainable electricity supply and result in the appropriate use of government financial funds for off-grid electrification in Type 3 and 4 communities in Colombia. This paper proposes two strategies: 1) a gradual repowering of existing generation capacity with renewable energy technologies as demand grows; and 2) a gradual reduction in tariffs in line with the falling cost of generation. To address the research aim, a simulation model was built using system dynamics and sustainability indicators to explore the impacts of different strategies under different scenarios. System dynamics was selected as this approach allows the incorporation of feedback loops (Sterman, 2000), which is necessary to represent the long-term interaction between electricity supply, electricity demand, generation system margin and generation system costs, making it possible to represent changes over time. For example, the installation of new generation capacity or growth in energy demand (Dyner, 2000).

The provision of sustainable energy for all is about more than just the provision of low-carbon, renewable energy sources (Garces et al., 2021; Tomei et al., 2020). Rather, it must also be affordable, reliable, environmentally benign and of sufficient quality. It is this conceptualization of "sustainable electricity supply" that is used here, via strategies that seek to provide 24-hour electricity that: facilitates the

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[1] Exchange rate: Average of the TRM for 2020 and 2019 ($ 3,487.23 COP/USD) (Banco de la República, n.d.).

development of productive activities, benefits the environment, communities and government funds, and lasts over time. To assess the sustainability of the strategies, this paper uses the same five dimensions of sustainability (environmental, economic, social, technological and institutional) as Garces et al. (2021). Finally, there is ample evidence - not least in the declining costs of solar and wind - that renewable energy should underpin electrification in off-grid areas (Boliko and Ialnazov, 2019; Diouf et al., 2013; Dyner et al., 2005; IRENA, 2019; Kumar et al., 2009); therefore, a starting assumption for this research is that renewable energy is used in off-grid areas of Colombia.

This is the first study to use system dynamics to assess and measure the sustainability impacts of different strategies to deliver and enhance electricity access in off-grid communities, and it, therefore, makes an important contribution to knowledge. While this research focuses on Colombia, the methods and findings are relevant to any country that is seeking to deliver sustainable, affordable and durable electricity to all, as the model and its results are based on two assumptions which are widely reported and validated in the literature for off-grid communities, i.e. the benefits of renewable installation and the potential for socio-economic development linked to electricity access. Thus, the novelty of this research lies in the development of a simulation model based on these two assumptions, which seeks to answer the following question: *how can a sustainable and durable electricity supply be provided in small off-grid communities in Colombia?*

The rest of this paper is structured as follows: Section 2 provides background information and the rationale for using system dynamics. Section 3 describes the methodology. Section 4 presents the modelling results and discusses the findings, including the impacts on the sustainability of different supply options. Finally, Section 5 draws some conclusions and discusses the policy implications of the research.

2. Background

The relationship between access to electricity on the one hand, and the sustainable development of off-grid communities on the other, is a central component in the formulation of the simulation model developed for this research. This relationship has been studied from different perspectives and using different methodologies. For example, research has examined this relationship by correlating access to electricity with indicators, such as Gross Domestic Product, and indexes such as the Human Development Index and Education Index (Alstone et al., 2015; Bhattacharyya and et.al., 2013; Jimenez, 2017; Kanagawa and Nakata, 2008). Other studies have merged existing frameworks, such as sustainable rural livelihoods, with mathematical modelling techniques such as system dynamics (Dyner et al., 2005; Franco et al., 2008) and optimisation approaches (Cherni et al., 2007; Henao et al., 2012). System dynamics, for example, has been used by Riva et al. (2018) and Riva and Colombo (2020) to characterize, describe and understand the nexus between electricity access and rural development in isolated settings.

Sustainable development is viewed here not as an outcome, but rather as a process (Nabavi et al., 2017). From this perspective, sustainable development is governed by two principles: (1) its final state cannot be predicted, as everything is highly intertwined and interconnected; and (2) it is constantly in development, as it responds to feedback from the system. In other words, the future state depends on actions that are taken today. These principles are closely related to those which govern system dynamics (Nabavi et al., 2017). Therefore, the use of system dynamics is appropriate for the simulation and modelling of issues such as access to electricity, sustainable development and their relationships in off-grid community contexts (Dyner et al., 2005; Franco et al., 2008; Hartvigsson et al., 2018; Riva et al., 2019, 2018; Riva and Colombo, 2020).

System dynamics (SD) is a rigorous modelling approach that allows observation of system behaviour over time through computer simulations of different scenarios, that can often be applied to any dynamic and complex system, with any time and spatial scale (Sterman, 2000). SD can be applied to a wide variety of topics ranging from the areas of health, education and security to the world of business and public policy-making (Kunc et al., 2018) reveals that SD encompasses research areas of both soft (qualitative) and hard (quantitative) nature. In addition to this, there is a strong tradition of research into behavioural aspects - where a key area of research is decision-making and organisational learning. Furthermore, SD has become a strong contributor in different application areas, among them energy policy and markets, and as such, SD enables understanding of the long-term effects of policies, strategies and decisions, helping to accelerate learning and enhance effectiveness by developing a better understanding of the system (Sterman, 2000).

Regarding the use of SD in off-grid electrification studies, it was found that Hartvigsson et al. (2018), for example, used SD to compare different capacity expansion strategies for rural mini-grids in Tanzania. Also Riva et al. (2019) and Riva and Colombo (2020) provide tools for projecting electricity demand in isolated rural areas through the conceptualisation of the determinants and complexities affecting the evolution of demand in such settings. As a result, this approach requires fewer quantitative data and provides a structured and holistic modelling framework – this is important for countries such as Colombia, where quantitative data for off-grid communities is limited.

SD is also recognised in the literature as a suitable methodology for social model simulation, as it adopts a systemic perspective to map value generation processes, integrating feedback loops, strategic resource accumulation and depletion processes, time delays and non-linear interactions (Cosenz et al., 2020). Likewise, SD has components such as level and flow diagrams, through which revenue and cost structures can be built. This approach has been used by Cosenz and Noto (2018) and Cosenz et al. (2020), who use these diagrams to assess business strategies over time. Finally, level and flow diagrams also allow the incorporation and measurement of sustainability indicators across different dimensions of sustainability. For example, Cosenz et al. (2020) incorporate indicators such as CO2 emissions to assess the environmental dimension, improved value for money for the economic dimension, and community development and well-being for the social dimension.

Regarding the use of SD and scenarios, one of the main strengths is that they can involve testing the robustness of various strategies in a dynamic but endogenous environment. Scenarios can also involve simulating the external environment and observing the performance path of a system under “business as usual” conditions. In such cases, a system does not determine external environment dynamics, but rather the external environment defines system performance (Torres et al., 2017).

On the other hand, one of the limitations or main challenges of SD is that it is a simulation tool through which it is intended to represent the decision-making of the modelled agents, which implies an exhaustive study of these agents and their interaction with their environment to justify and model their behaviour and decision-making in the best possible way (Greasley and Owen, 2016). To address this limitation, an exhaustive review was made of the public policy governing the actions of ESPs in the ZNI, and field visits were also undertaken, through which it was possible to gain first-hand knowledge of the behaviour of both generating agents and users, which is reported in Garces et al. (2021). It is worth mentioning that the premise of energy transition through hybrid microgrids (diesel, solar panels and batteries) that governs the model is aligned with national public policy. However, one of the limitations of this study is that it does not include other renewable electricity generation technologies. In addition, the study is limited to the financing mechanisms offered by the Colombian government in the ZNI and through the service charge, so there could be an opportunity to incorporate other financial mechanisms. It can also be seen as a limitation that the study is done in a general way through a case study in which the localities of Type 3 and 4 are represented, but it is not an application to a specific community.

Regarding the development of the dynamic hypothesis, a key starting point is the concept of the "energy poverty trap" (Dyner et al., 2005). This concept is associated with reinforcing loops (see Figure 1), that are perpetuated over time and which condemn isolated rural communities to remain trapped in energy poverty (Dyner et al., 2005) when denied access to electricity - an essential element of contemporary development. This means that the poorer the community, the lower the energy demand, which, in turn, reduces energy supply and induces poverty – hence the energy poverty trap.

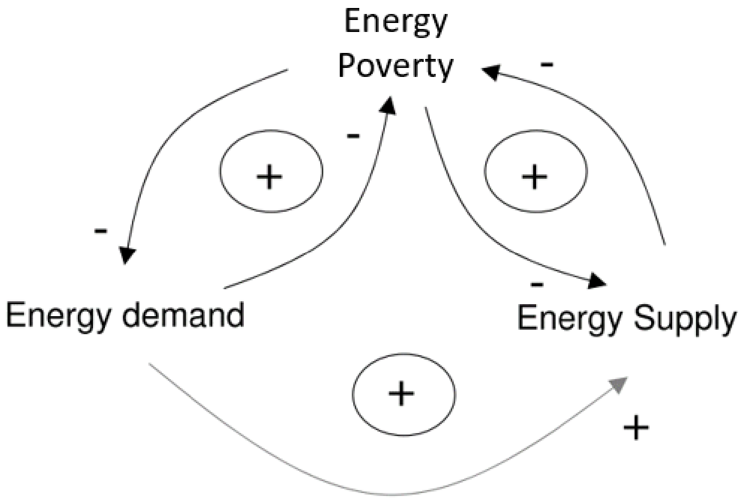


Figure 1. The energy poverty trap. Source: Authors' adaptation from Dyner et al. (2005).

However, the energy poverty trap may be alleviated if other aspects or actions are considered. This may include economic activities, which can result in a greater household or community income, providing the means to acquire and maintain energy infrastructure and thus reducing energy poverty. In this sense, economic and productive activities are one potential option for improving the welfare of communities (Cherni et al., 2007; Garces et al., 2021; Kanagawa and Nakata, 2008; Mandelli et al., 2016). Another aspect is that of community uses, wherein access to electricity supports the development and social wellbeing of off-grid communities by facilitating improvements in, for example, electricity in health centres and schools, community centres and street lighting (Cherni et al., 2007; Dyner et al., 2005; Garces et al., 2021; IEA, 2017; Tomei et al., 2020). Community uses can therefore result in improvements to people's quality of life, including in terms of health, nutrition and use of time; for example, by eliminating drudgery individuals should have more time to spend on education, skills development and recreation (Garces et al., 2021; IEA et al., 2020).

3. Methodology

To answer the research question posed in the introduction, a three-step methodology was used. The first step is the construction of a simulation model using SD, which is specified in Section 3.1. The second step is the definition of the scenarios, strategies and cases to be evaluated through the simulation model, and these are defined in Section 3.2. Finally, Section 3.3 defines the sustainability indicators that were incorporated into the model to measure the performance of each of the strategies defined in Section 3.2.

3.1 Modelling approach

The first step in the construction of the simulation model is the development of a dynamic hypothesis or conceptual causal model (see Figure 2), which is built from a set of constructs and their linkages discussed in the literature (summarised in Appendix A). The hypothesis set out in Figure 2 proposes that the gradual expansion of off-grid electrification systems – via renewable energy technologies – supports socio-economic development in off-grid communities, either due to increased hours of access or the provision of electricity access itself. This in turn facilitates the provision of a sustainable and durable, i.e. long-term, electricity supply. The dynamic hypothesis depicts the interactions between power capacity, demand, margin, electricity supply, and productive activities through a causal diagram made up of six loops: two balancing loops (B1 and B2), and four reinforcing loops (R1 to R4). These loops represent the balancing and reinforcing feedback mechanisms that constitute the system under study i.e., electricity access in off-grid communities.

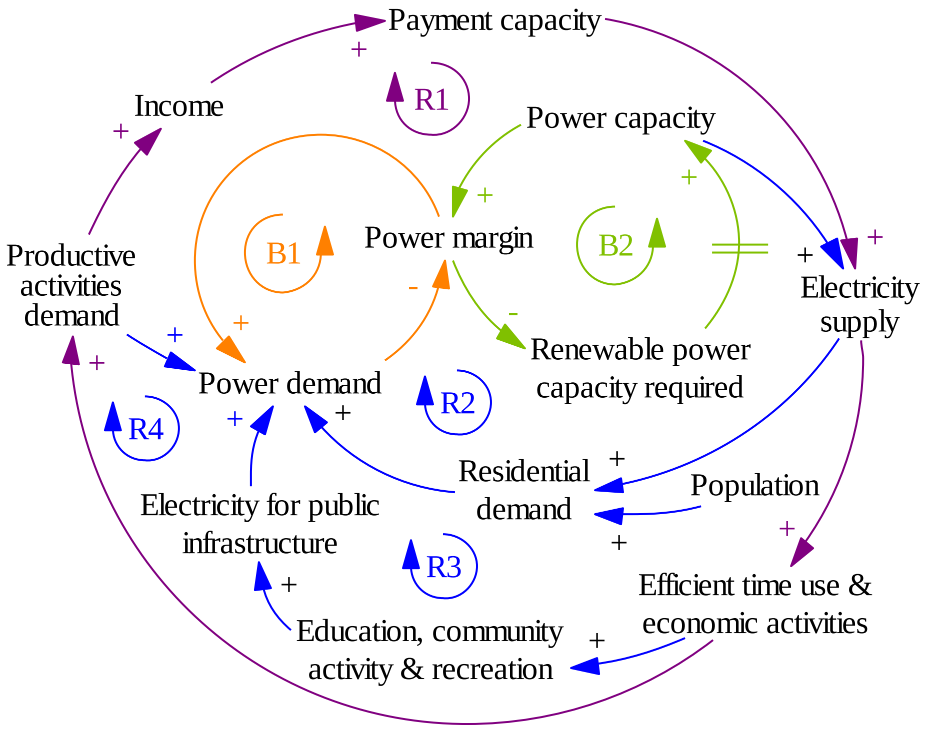


Figure 2. Global aspects of sustainable electricity supply in off-grid communities. Source: Authors' own.

Loops R1, R2, R3 and R4 have a positive reinforcing effect on the system. Loop R1 (production) indicates that with more productive activities, community incomes grow, which means that users have increased ability to pay for electricity. In turn, this means that the ESP will also have greater financial revenue, which increases the likelihood of investment in electricity supply. Increased electricity supply in off-grid communities has an impact on time use efficiency and also on the development of economic activities (Garces et al., 2021; IRENA, 2019), which leads to an increase in electricity demand in homes and community spaces, and in economic and productive activities, generating a positive reinforcing effect for the community and the ESP.

The R2 to R4 loops show how the community develops with a greater supply of electricity; these three cycles are explained jointly as they all share a similar structure and behaviour, with similar impacts on demand growth and community development. These loops show that as the hours of electricity supply are extended, the community can use their time more efficiently and have access to better conditions for work and education, which could lead to greater skills for entrepreneurship - an important factor in the development of productive activities (Hartvigsson et al., 2021; Narula and Bhattacharyya, 2017). Many productive activities require electricity and as they grow so does demand; growing power demand leads to a narrowing of the power margin, requiring greater installed capacity (loop R4 - Figure 2). A similar situation occurs for residential demand – which also grows with population growth (loop R2 - Figure 2) – and community services or community demand (loop R3 - Figure 2), where greater electricity supply facilitates new uses in schools, health centres, public lighting, among other services, which improve quality of life in off-grid communities.

Figure 3 shows the balancing loops. Loop B1 shows how the power margin gives a signal for demand growth. In other words, the higher the power margin, the more capacity it must cater for in terms of new household, community and/or productive uses of electricity. Despite the amplifying relationship, this loop has a balancing effect because, as electricity demand grows, the power margin is reduced, and therefore productive activities and power demand have less possibility of growth as the system begins to reach its limit, evidencing the need for new power capacity. This is where loop B2 comes in, because when the power margin is large (> 1), no new installed capacity is required, but when the margin is small (<1) or starts to shrink, new renewable power capacity needs to be installed, extending the power margin. These two balancing cycles are associated with oscillatory tracking behaviour, and together generate a reinforcing effect on the system.

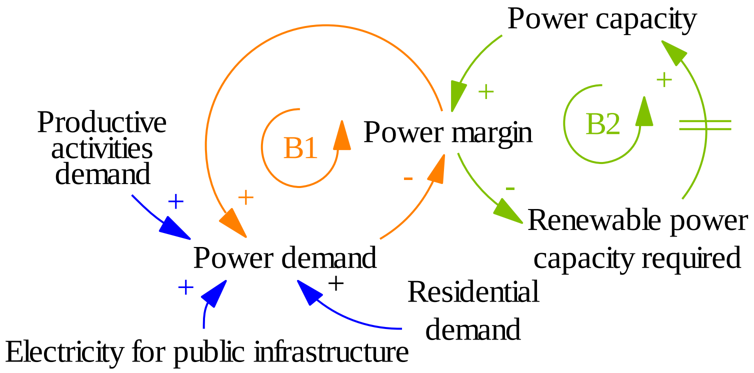


Figure 3. Causal relationships between demand, margin and power capacity. Source: Authors' own from Dyner (2000).

Based on the dynamic hypothesis, a simulation model was constructed to represent a hybrid microgrid system comprising diesel, solar PV and lithium batteries - the latter with an average lifetime of 10 years (IRENA, 2017b). Diesel technology is considered here since around 95% of off-grid communities in Colombia are served by diesel generation plants (SSPD, 2018). Solar PV technology is considered for its modularity, since one assumption of the simulation model is that the system gradually expands using renewable energy technologies, and this requires a technology that allows such expansion. In addition, Colombia has an adequate level of radiation throughout its geographical area - on average 4.5 kWh/m^2 per day (IDEAM, 2020). The simulation horizon is set at 22 years as this provides an appropriate timeframe to observe how the initial life cycle of a hybrid microgrid system may contribute to the sustainable development of off-grid communities (Huneke et al., 2012; Vides-Prado et al., 2018). The financial sustainability of the system is also analysed, particularly the replacement of parts and repowering of the microgrid. The model was built using Powersim software and consists of three main blocks: (1) electricity demand; (2) installed capacity and generation; and (3) cash flows and repowering. These are described in full in Appendix B. To validate the simulation model, we followed the methodology proposed in Barlas (1994), where three blocks of tests are proposed: direct structure tests (structure validation, dimensional consistency and parameter verification); performance-oriented structure tests (extreme conditions and sensitivity analysis) and performance validity tests. These tests are detailed in Annex D of Garces (2021). It is important to mention that during the process of building the model, interviews with experts and visits to ZNI communities with hybrid microgrids (diesel, solar panels and batteries) were carried out to support the development of a model that is close to reality.

3.2 Development of scenarios, strategies and cases

Four scenarios were proposed, which considered two financing dimensions: (1) with and without tariff subsidies for operation expenditure (OPEX); and (2) with and without external financing for capital expenditure (CAPEX) (see Figure 4). These scenarios are aligned with the two key funds that support electricity access in off-grid communities in Colombia – FSSRI and FAZNI – and which were described in the introduction (Garces et al., 2021; MME, 2020; Presidencia de la República, 2001).

The simulation model has a dashboard through which each scenario can be set using two binary parameters. "Request EF CAPEX" is for requesting or not requesting external financing (EF) to install new generation capacity, where 0 indicates no request and 1 indicates that financing is requested. “% Tariff subsidy” indicates whether or not the community has a tariff subsidy, where without subsidy it is 0 and with subsidy it is 0.83 (which is the typical percentage in communities of fewer than 150 users). The scenarios are as follows:

- **TSO - Tariff Subsidy Only, no external financing for CAPEX**: This scenario is linked to FSSRI, which guarantees a subsidy to the ESP to provide electricity supply to low-income users (Garces et al., 2021). Under this scenario, the ESP receives subsidies under FSSRI, but no external financing for CAPEX. % Tariff subsidy = With subsidy, Request EF CAPEX = No

- **EFC - External Financing for CAPEX, no tariff subsidy:** This scenario is linked to FAZNI, through which the construction of new installed capacity in off-grid communities is financed (Garces et al., 2021). In this scenario, the ESP receives external financing for CAPEX, but there is no tariff subsidy (i.e. no FSSRI). % Tariff subsidy = Without subsidy, Request EF CAPEX = Yes

- **NSNEF - No Subsidy and No External Financing:** In this scenario, the ESP does not receive any support, i.e., it operates and invests in new installed capacity using its financial resources. This scenario draws on neither FAZNI nor FSSRI. % Tariff subsidy = Without subsidy, Request EF CAPEX = No

- **TSEFC - Tariff Subsidy and External Financing for CAPEX:** In this scenario, the ESP receives finance for CAPEX and a subsidy to provide electricity to low-income users. This scenario implies the use of both FAZNI and FSSRI. % Tariff subsidy = With subsidy, Request EF CAPEX = Yes

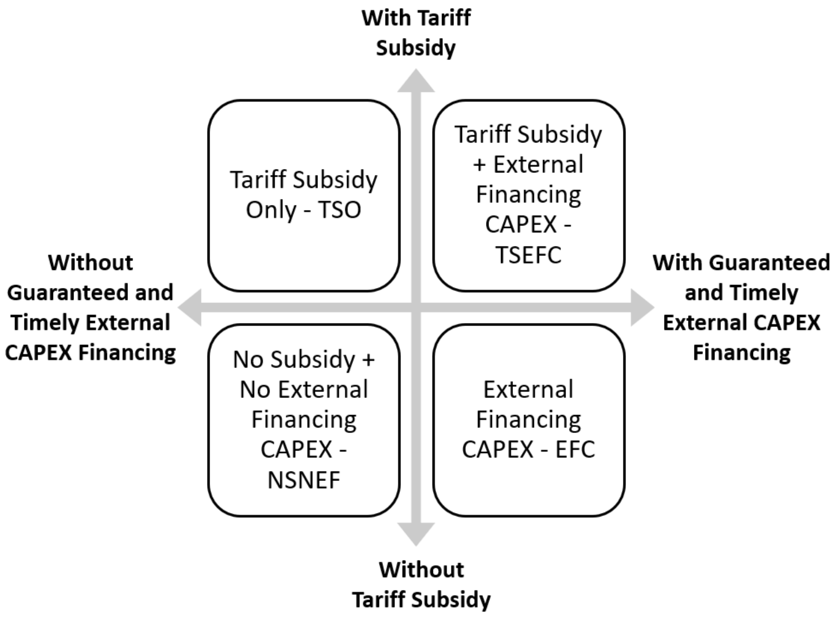


Figure 4. Scenarios for strategy evaluation. Source: Authors' own from Garces et al. (2021).

Under these scenarios, two strategies are evaluated:

- **Strategy 1 (S1) - Expansion with Renewables:** This strategy is incorporated into the model as a decision rule whereby new renewable energy capacity is installed to replace diesel and to meet community demand. If new installed capacity is required, as the margin of the system is lower than the desired margin, the model estimates how much new installed capacity is required and its cost (which according to the model's assumption will be covered by solar panels and batteries). Then, this value is compared with the funds available for expansion. If the funds are sufficient, the total new capacity is installed; if not, what can be paid for with the available funds is installed (under some scenarios, external financing is used to build the total required). In addition, hours of electricity supply are gradually increased to 24 hours of continuous service, which also incentivises the gradual and continuous replacement. Additionally, diesel generation is reduced annually by 5% so that by 2040 diesel use is zero. The system becomes economically sustainable thanks to the savings from subsidies as diesel use, and thus variable costs, decrease, which allows for increased funding for new renewable installed capacity.

- **Strategy 2 (S2) - Reduction in CU:** The incorporation of solar PV and battery storage (dependent on S1), which have learning curves in their costs, makes it possible to reduce the CU (reduced

OPEX). Since the unit cost is lower, a reduction in subsidies is possible. This has a benefit for the government (less subsidy is required), and no impact on the ESP, while households have the same, or reduced, cost of electricity (depending on the ESP). To model these changes, we assume a 10% reduction in subsidies every five years. This approach draws on existing Colombian regulations which require an evaluation of electricity costs every five years - Article 126 of Law 142 of 1994 on Domiciliary Public Services (Congreso de Colombia, 1994).

To measure the performance of these two strategies under the proposed scenarios, the simulation model is parameterised using information from Type 3 and 4 localities. As mentioned in the introduction, these localities are characterised by low-income residential users (SUI, 2019b), typically have less than five hours of electricity supply (usually by diesel) (SUI, 2019a), and average subsidy percentage rates of 83.8% (Type 3) and 81.2% (Type 4). The model is based on a 'typical' Type 3 or 4 community with 30 households, street lighting, a school, a health centre, and a community centre; and where electricity is provided for four hours per day by a diesel generator. The simulation begins with residential load curves and public infrastructure with electricity supplied from 6 pm to 10 pm, and total daily demand of 17.22 kWh / day and a peak demand of 4.71 kW. Appendix C summarises the most relevant model parameters. In addition, the model has indicators to make it easier to measure and compare the sustainability performance of the strategies under the different scenarios - these are described in the Section 3.3.

Finally, SD allows 'what if?' questions to be asked of results. In this paper, four 'what if?' cases are examined:

- **Case 1 (BAU)**: Examines the 'typical' community under the TSO scenario, without the proposed strategies. Here, the community is provided with four hours of electricity supply through a diesel plant during the entire 22 years of the simulation. In addition, it has an operating subsidy through the CU, but no access to FAZNI. This scenario could be considered a business as usual (BAU).

- **Case 2 (Baseline)**: Examines the same community, but both strategies (S1+S2) are implemented under the TSFEC scenario. This means that the generation system is repowered with new renewable energy installed capacity.

- **Case 3 (Reducing surplus):** This case arises from the results obtained in Case 2, where the joint application of the two strategies under the TSFEC scenario generates a financial surplus. It explores how this surplus might be reduced – to decrease dependence on subsidies and benefit users and government alike – asking "what if the CU reduction curve is adjusted?".

- **Case 4 (Faster expansion with renewables):** This case answers the question "what if renewable installed capacity is introduced from the first simulation period, even if the system margin does not signal that new capacity is required?". The results presented are those related to the TSFEC scenario, together with the implementation of the two strategies.

3.3 Measuring the sustainability of the system

A final component of the research was to understand the environmental, technological, institutional, economic, and social sustainability of the system over time. Building on the authors' earlier research (Garces et al., 2021), this study used the same set of dimensions to evaluate the performance of the microgrid system and the outcomes of different strategies for electricity service provision. Table 1 sets out the indicators included in the model.

Table 1. Sustainability indicators considered in the simulation model.

Dimension	Indicator Code	Indicator name	Unit	Indicator description
Environmental	ENV1	CO2 Generated	Tons CO2	Tons of CO2 equivalent per kWh of diesel generation
Technological	TEC1	Solar Generation	%	% Total solar generation vs. total generation
Institutional	INS1	Average Cost of Government Contributions (ACGC)	US$/ kWh	Average costs resulting from dividing the total subsidies + funding for CAPEX by the total generation for the whole simulation
Economic	ECO1	Average Cost of Electricity Supply (ACES)	US$/ kWh	Average cost resulting from dividing the total system cost by the total system generation for the whole simulation
	ECO2	Total System Cost (TSC)	US$	Sum of OPEX for the whole simulation + sum of replenishment expenditure for the whole simulation + sum of CAPEX for the whole simulation. Helps determine which strategy leads to lower overall system cost
	ECO3	Total OPEX	US$	Sum of OPEX expenditures over the entire simulation period
	ECO4	Surplus	US$	The sum of all the financial resources available to the ESP once operation, replacements and repowering costs are met. This indicator enables the identification of whether the % decrease in the tariff of S2 can be accelerated and how rapidly this can occur
	ECO5	Productive Activities Demand vs Total Demand (% PAD vs TD)	%	% Share of demand from productive activities with respect to the total demand of the system
Social	SOC1	Community Weighted Average Tariff (CWAT)	US$/ kWh	The average of total collection revenue divided by total system generation for the entire simulation
	SOC2	Per Capita Demand (PCD)	kWh/ person	The amount of electricity consumed per person per annum

4. Results and Discussion

This section presents the results associated with the four cases described in Section 3.2. The full results are summarised in Appendix D. It is important to clarify that the pattern of linear change in the figures is due to different decision criteria that were incorporated into the model to make it more realistic. For example, the construction of new installed capacity is not conducted smoothly over time, rather this is achieved through a minimum project expansion size to cover several periods of time according to the signals given by the model itself, which makes the potential generation behave in a discrete rather than continuous manner. Due to the difficult access to these communities, the continuous installation of new generation capacity is not viable.

4.1. Case 1 vs Case 2

Figure 5 shows the results of Cases 1 and 2. For Case 1, there is no expansion in generation, as illustrated by the green line in Figure 5A. Generation is limited in Case 1 because the system can only supply four hours of subsidised service through a diesel generator, which limits the operation of the ESP due to insufficient funds being available to grow the system. The limited hours of electricity supply also limit the community's ability to undertake productive activities, which keeps communities in an energy poverty trap.

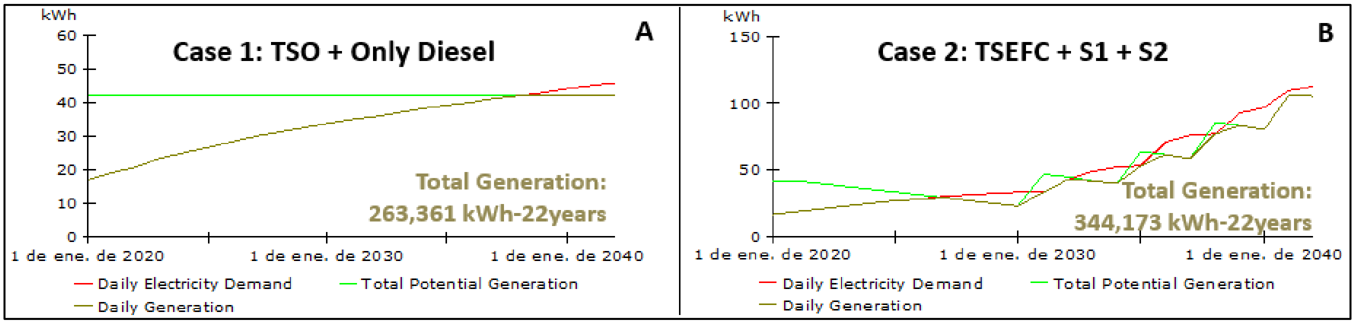


Figure 5. Potential generation, electricity demand and generation of Case 1 vs. Case 2. Source: Authors' own.

Conversely, in Case 2, where external financing is available for the installation of new generation capacity, both potential generation and demand grows (see Figure 5B). This growth is due to the gradual installation of solar panels and batteries, which in turn facilitates the increase of electricity supply from four to 24 hours per day. The installation of new renewable generation is due to the annual decrease in diesel (see the first ten years of the green line in Figure 5B) and the availability of external financing. In Case 2, both strategies result in a better performance across all sustainability indicators when compared to Case 1 (see Table D.1 Appendix D), and help to free the community from the energy poverty trap through benefits such as the creation of productive activities (ECO5) and higher per capita electricity demand (SOC2). This scenario also offers other benefits such as a decrease in CO2 emissions (ENV1) and a reduction in OPEX (ECO3) and total system cost (ECO2) (see Table 2).

Table 2. Breaking out of the poverty trap: Case 1 vs. Case 2.

Indicator **Cases**	**ECO5: PAD vs TD (%)**	**SOC2: PCD (kWh/person)**	**ENV1: CO2 Gen (Ton CO2)**	**ECO3: Total OPEX (US$)**	**ECO2: Total System Cost (US$)**
Case 1	0	66.75	192.94	112,090	112,090
Case 2	6	164.45	93.43	62,396	107,240

These results indicate that to improve electricity supply in off-grid communities and enhance the sustainability of the system, it would be prudent to install renewables and phase out the use of diesel. This latter strategy would also provide a means to pay for system expansion with renewables, as expenditure on diesel would fall. Analysis of the economic sustainability of the two cases reveals a reduction in "Total System Cost" (ECO2) (see Table 2), which falls from US$ 112,090 in Case 1 to US$107,240 in Case 2. However, the decrease in OPEX (ECO3) is more noteworthy and falls from US$

112,090 in Case 1 to US$ 62,396 in Case 2. This decrease can be attributed to the reduction in the use of diesel and the installation of solar panels and batteries. These results demonstrate that the cost of operating and maintaining a diesel system, which operates for just four hours per day, is higher than the costs of repowering the system with solar PV and batteries, which results in a system that would become capable of operating for 24 hours per day during the simulation period. Furthermore, the difference in total OPEX between the two cases[2] is sufficient to cover the US$ 44,844 required for CAPEX and replacements in solar PV and batteries in Case 2 (see Table 3). This means that external financing for CAPEX could be recovered in the 22 years of operation – providing the use of diesel is reduced to zero, as outlined in Strategy 1.

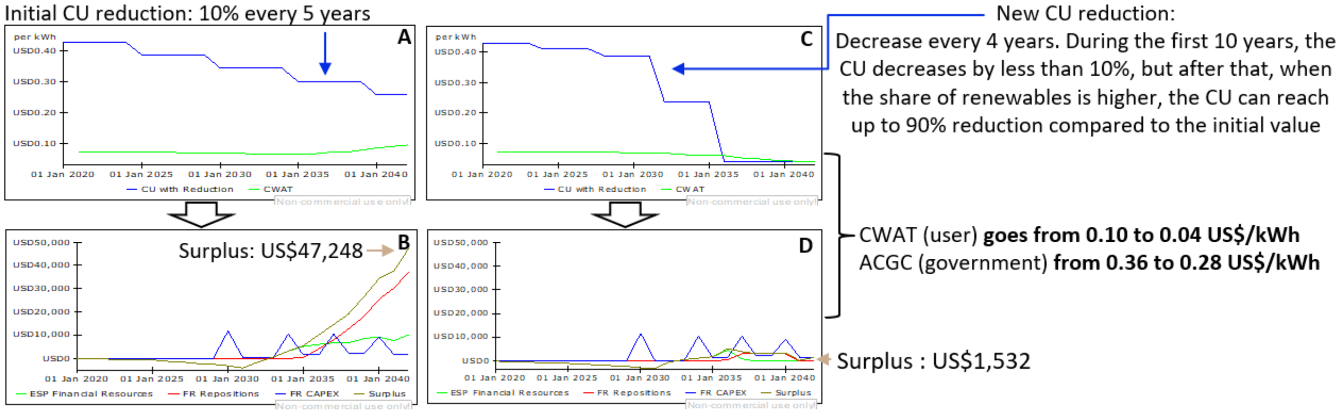
Table 3. CAPEX for solar PV and batteries and the cost of replacements for Case 2.

	2030	2034	2037	2040	Total
CAPEX S+B	$ 11,631	$ 10,437	$ 10,391	$ 9,232	$ 41,690
Replacements S+B				$ 3,154	$ 3,154

Under the technological dimension, the percentage of solar generation (TEC1) increases from 0% in Case 1 to 63% in Case 2 (see Table D.1 Appendix D). This shift in generation also has environmental benefits through reduced CO2 emissions (see Table D.1 Appendix D).

4.2 Case 3

For Case 3, different approaches were evaluated to reduce the financial surplus, whilst also maintaining good performance across the sustainability indicators (Figure 6D). The analysis revealed that the CU is reduced every four years; during the first 10 years, the CU decreases by less than 10%, but after that, when the share of renewables is higher, the CU can reach up to 90% reduction compared to the initial value (see Figure 6C). This reduction in the CU results in a reduction in the Community Weighted Average Tariff (SOC1) indicator from 0.10 to 0.04 US$/ kWh and a decline in the Average Cost of Government Contributions (INST1) indicator from 0.36 to 0.28 US$/ kWh. This shows that a reduction in CU has benefits for both the community and the government - without affecting ESPs. The former by reducing the cost of electricity, and the latter by a reduction in subsidies.



Initial CU reduction: 10% every 5 years

Surplus: US$47,248

New CU reduction:
Decrease every 4 years. During the first 10 years, the CU decreases by less than 10%, but after that, when the share of renewables is higher, the CU can reach up to 90% reduction compared to the initial value

CWAT (user) **goes from 0.10 to 0.04 US$/kWh**
ACGC (government) **from 0.36 to 0.28 US$/kWh**

Surplus : US$1,532

Figure 6. New Unit Cost of Service Provision (CU) reduction and its impacts. Source: Authors' own.

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[2] Total OPEX Case 1 – TOTAL OPEX Case 2 = US$ 112,090 – US$ 62,396 = US$ 49,694.

4.3 Case 2 vs. Case 4

To complement the analysis, the performance of the ‘typical’ community was evaluated by installing 13.5 kW of solar PV and batteries from the start of the simulation. Figure 7B shows how the performance of the system improves under Case 4 with respect to Case 2 - where the transition to renewables is gradual (see Figure 7A). This improved performance is also revealed through sustainability indicators; for example, the percentage of productive activities (ECO5) increases from 6% to 20%, and per capita electricity consumption (SOC2) goes from 164.45 to 317.80 kWh/ person (see Table D.1 Appendix D). This is due to the wider generation margin, which makes it possible to develop more productive activities thus encouraging growth in demand. In addition, the usage rate of renewables (TEC1) increases from 63% to 91%, which further reduces CO2 emissions (ENV1) – even though more electricity is being generated. Finally, the "Average Cost of Electricity Supply" (ECO1) reveals that overall system performance is also improved; falling from 0.43 US$/kWh in Case 1 to 0.18 US$/kWh in Case 4 (see Table 4). This indicates that more electricity is being generated for longer hours at a lower cost.

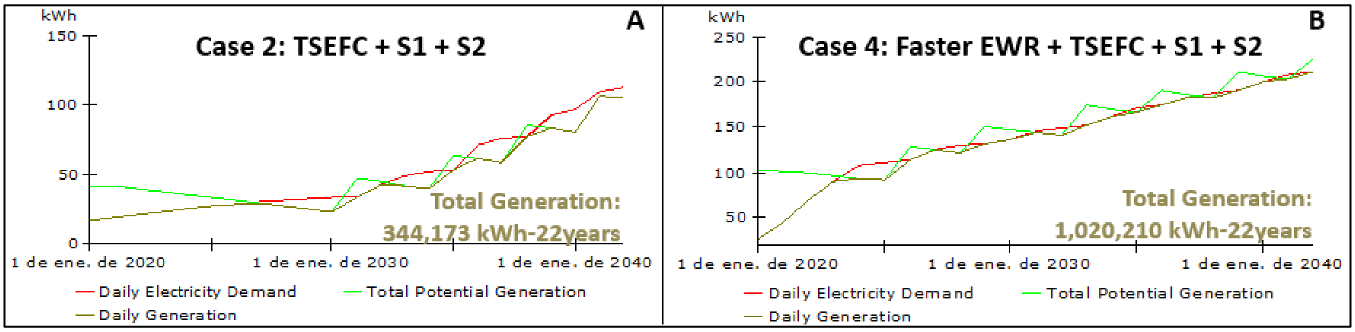


Figure 7. Potential generation, electricity demand and generation of Case 2 vs. Case 4. Source: Authors’ own.

4.4. A cross-case comparison

The reduction in the average cost of electricity supply across all the cases is shown in Table 4. To support this reduction, public policies are required that support the use of renewable energy technologies in off-grid areas and disincentivise the use of diesel. Table 4 also shows that the faster the installed renewable capacity comes on stream, the better the performance (i.e. Case 4). This result supports the Colombian PIEC which, as discussed in the introduction, aims to install stand-alone and hybrid systems in locations not yet served by electricity. Furthermore, these results highlight the importance of making the transition to renewables as soon as possible given the substantial cost reduction.

Table 4. Total Cost, Total Generation and Average Cost of Electricity Supply for the different cases.

Cases	Total Cost (US$)	Total Generation (kWh)	ECO1: ACES (US$/ kWh)
Case 1	$112,090	263,361	0.43
Cases 2 and 3	$107,240	344,173	0.31
Case 4	$188,434	1,020,210	0.18

Table 5 reveals that across the different cases, government subsidies to off-grid communities continue to be required. For Case 1 this amounts to a subsidy of 0.36 US$/kWh; however, when renewables are added to the generation mix this requirement falls to 0.28 US$/kWh in Case 3 and 0.12 US$/kWh in Case 4. As a result, although subsidies will likely still be required for the foreseeable, the integration of renewable energy technologies reduces the amount of subsidies needed. Table 5 also shows that the

0.36 US$/kWh given by the government in Case 1 to subsidize the operation (INS1), is sufficient to cover the total cost of the electricity supply (ECO1) in Cases 3 and 4 (0.31 or 0.18 US$/kWh). In other words, the support currently provided by the Colombian government to operate diesel plants for a few hours of electricity supply per day will be more than enough to operate, maintain and upgrade to a hybrid system.

Table 5. Average Cost of Electricity Supply, Average Cost of Government Contributions, and average tariff.

Cases	ECO1: ACES (US$/ kWh)	INS1: ACGC (US$/ kWh)	SOC1: CWAT (US$/ kWh)
Case 1	0.43	0.36	0.07
Case 2	0.31	0.36	0.10
Case 3	0.31	0.28	0.04
Case 4	0.18	0.12	0.07

These results indicate that the Colombian government will need to maintain subsidies to off-grid communities, but that, by integrating renewable energy technologies, this contribution could be significantly reduced. Under the different cases, the cost of electricity to the community stays largely the same. While SOC1 declines slightly from 0.07 US$/ kWh in Case 1 to 0.04 US$/ kWh in Case 3, it remains the same as Case 1 in Case 4 (0.07 US$/ kWh). This means that the community will benefit from longer hours of electricity supply for the same cost.

The analysis has also shown that phasing out diesel leads to significant savings in OPEX and reduces the overall system cost. By comparing Cases 3 and 4, it is evident that the sooner the transition is made, the better the system will perform, with knock-on benefits to all stakeholders (i.e. the ESP, communities, and the government). It is therefore important that the Colombian government accelerates the installation of renewable energy technologies in communities that a) currently do not have access to electricity, and b) rely on diesel generators, to eliminate the use of diesel as soon as possible - according to simulations it is possible to reach zero diesel by 2040.

The different cases show that the installation of renewable generation capacity in communities with limited electricity service, together with the implementation of the other strategies (e.g. increased hours of service, and decreased use of diesel), increases electricity demand and improved the overall system performance. This validates the hypothesis because an ESP's business model is dependent on the sale of electricity. By making it viable for the ESP to increase electricity supply - through renewable sources - communities can develop and enhance productive activities, thus increasing electricity demand (and enhancing sales for the ESP) and improving the capacity of users to pay for that new demand. Thus, this creates a virtuous circle which alleviates the energy poverty trap.

Finally, to ensure that solar energy can meet electricity demand, after gradually replacing diesel power generation, the use of battery banks is essential; storage enables 100% renewable mini-grids (IRENA, 2019, 2017b) - something that is expected to be feasible considering the forecasts of lower prices and higher efficiency (IRENA, 2017b). It was also noted that the success of a 100% renewable system depends on the quality of the batteries, and the required maintenance and replacement of the different components (Garces et al., 2021) – this is why the model includes savings for replacements and repairs, intending to make the system sustainable in the long term. Indeed, one of the main novelties of the study is to show that small ZNIs can have a sustainable electricity supply through the gradual transition of diesel until 100% renewable generation systems are reached. In addition, as electricity supply in small ZNIs is so poor (less than 5 hours per day), this gradual approach ensures that demand is met sustainably as the installed renewable capacity is increased gradually and in advance (by having the desired margin). Furthermore, the use of renewables allows savings to be generated for replacement and repowering of the renewable system, savings that could not be generated with the use of diesel. At last, the increase in hours of service provision facilitates the socio-economic development of the communities, which has an impact on greater electricity demand and therefore more income for the ESP, generating a development path for both the ZNI and the companies that provide the electricity service in these places.

5. Conclusions and Policy Implications

In this paper, we described a system dynamics simulation model that was developed to explore how different strategies impact the sustainability of electricity supply in off-grid communities in Colombia. Four scenarios were developed, which aligned with two key funds that support electricity access in Colombia – FAZNI for CAPEX and FSRRI for OPEX. The results of the simulations enable us to draw three key conclusions. First, for off-grid communities, a transition from diesel generators to hybrid systems which incorporate renewable energy technologies, such as solar PV with batteries, is not only possible but also economically viable and desirable. Second, to improve electricity service in off-grid communities and make their electricity supply sustainable, the transition to renewables should be made as soon as possible. The transition should be accompanied by the strategies analysed here, which included achieving the complete phasing out (zero use) of diesel by 2040, provision of increased hours of electricity service via renewable energy, and reducing CU. The analysis shows, however, that these strategies should be implemented gradually, because a decrease in diesel without sufficient installed renewable capacity could, for example, lead to blackouts. The results also show that, once a hybrid system is in place, new renewable installed capacity can be added gradually in line with demand growth. Third, the simulation model indicates that the Colombian government should seek to shift the status quo away from the use of diesel and towards renewable energy. Every year of continued use of diesel plants is a year in which public money is misused through subsidies for the operation of diesel plants. This paper has shown that the use of renewable energy technologies can not only provide more hours of electricity service but also enhance the sustainability of the system across multiple dimensions. However, part of the success of the proposed strategies is due to the financial support that the country offers through FAZNI and FSSRI. These funds are essential to reach full electrification in Colombia and must be maintained; however, implementation of the proposed strategies would reduce dependence on these funds whilst delivering other system benefits.

The results highlight the need to speed up the energy transition in Colombia’s off-grid communities, especially in Type 3 and 4 localities which typically have a poor and expensive electricity supply. This transition in turn requires adjustments to existing policy and regulations, which can respond to the changes brought about by the transition to renewable energy technologies in these areas. For example, one of the regulatory adjustments that can be foreseen through the simulations relates to electricity subsidies. In Type 3 localities (i.e. <150 users), subsidies cover around 80% of CU, i.e. the cost of providing electricity service through diesel plants, which guarantees no more than five hours of electricity supply per day. With a transition to renewables, the cost of service provision decreases to around 0.25 US$/kWh, which indicates that the ESPs would need lower subsidies for OPEX. Thus, the Colombian government should plan what to do with the money that the ESPs will not require as a result of this transition. Options might be to cover CAPEX and future replacements of new installed renewable energy capacity, and/or to support the socio-economic development of off-grid communities. This last option would support the maintenance of a virtuous cycle of growing electricity demand and users’ ability to pay.

Finally, the energy poverty trap is not only a challenge for off-grid communities in Colombia. Around the world, millions of people face the same problem – they live without access to electricity, or have only a few expensive hours of electricity supply provided through diesel generators. This presents a major challenge to efforts to undertake productive activities and improve the economic, social and environmental well-being of off-grid communities around the world. Although a few hours of service are better than no hours of service, it is clear that limited electricity – provided by diesel generators – remains a key factor in keeping communities in an energy poverty trap. Given that the benefits of renewable energy are well known, it makes little economic sense to supply just a few hours of electricity through diesel plants, using subsidies to cover their high operational costs. Furthermore, the provision of infrastructure alone will not be sufficient to drive the sustainable development of communities. Rather, and as the results have illustrated, the provision of electricity must go hand-in-hand with other initiatives to support the socio-economic development of the communities – for productive activities, as well as services, such as education and health. This requires not only accounting for today's demand but also anticipating and planning for tomorrow. Only in this way can access to sustainable electricity promote the virtuous circles that provide communities with a way out of the energy poverty trap.

Appendix A

Table A.1 details the explanation of the main concepts that make up the causal model (see Figure 2) in a similar way to that outlined in Rocha et al. (2020).

Table A.1. Constructs and relationships considered in the causal model.

Construct	Description	Ref	Verbal description of the equation
Power margin	A measure of the relationship between demand and generation capacity.	(a)	This results from the following calculation: generation capacity minus the demand, divided by the demand. The greater the generation capacity the greater the margin, and the more demand the lesser the margin.
Power capacity	The total installed generation capacity in the community from both non-renewable (diesel) and renewable energies.	(a)	In the simulation model, generation capacity is represented by levels which grow by the construction of new installed capacity (renewable only).
Renewable power capacity required	The installed renewable capacity that needs to be incorporated into the generation system due to a decrease in the margin.	(a)	This results from comparing the current margin with the desired margin, identifying whether the installation of new generation capacity is required – which according to the premise of the model will be covered by PV.
Power demand	The electricity demand of the community.	(a)	This is the sum of residential demand, public infrastructure demand and demand for productive activities.
Residential demand	The electricity demand of residential users.	(b) and (c)	This is calculated as the hourly demand of a residential user multiplied by the number of residential users in the community.
Electricity for public infrastructure	The electricity demand of public infrastructure, including public lighting, health centres, and educational institutions.	(b) and (c)	In communities of less than 150 users, community uses are few and are generally limited to street lighting, a school, a community centre and in some cases a health centre (these four uses are included in the model).
Productive activities demand	Electricity demand used for productive activities such as agriculture or cold storage.	(b) and (c)	In the model, there are different load curves according to the uses (cold chain, transformation, tourism) that can occur depending on the type of community (fishing, agriculture or tourism) and the hours of electricity supply that the community has.

Construct	Description	Ref	Verbal description of the equation
Income	The household income generated from productive activities.	(d) and (e)	The model has a parameter for average household income (which is set according to the community). In addition, there is a variable that estimates an increase in income per dwelling as productive activities are incorporated and electricity consumption increases, following the equation reported by Kanagawa & Nakata where GDP is associated with per capita electricity consumption.
Electricity supply	The electricity that is generated to supply electricity demand.	(a)	Generation by technology occurs according to the dispatch, which considers demand and supply (see Figure B.3. of Appendix B).

Sources: (a) Dyner (2000), (b) Mandelli et al. (2016), (c) Riva and Colombo (2020), (d) Kanagawa and Nakata (2008), (e) IRENA (2019)

Appendix B

The three blocks that make up the simulation model are described below.

1. Electricity demand

Electricity demand is made up of three components: residential demand, public infrastructure demand and demand for productive activities. Daily electricity demand is estimated by summing up the 24 components of the total load curve which groups the three demand components, as follows:

$$\text{Daily Electricity Demand} = \sum_{\text{h}=0}^{\text{h}=23} \text{Load Curve Total}_{\text{h}}$$

Where:

$$\text{Load Curve Total}_{\text{h0}} = \text{LC Residential}_{\text{h0}} + \text{LC Public infrastructure}_{\text{h0}} + \text{LC Productive activities}_{\text{h0}}$$

The behaviour of the three demand components depends on the number of hours of electricity supply. When the hours increase, demand has incentives to grow. For each of the demand components, there are reference load curves through which the shape of the load curve transforms over time according to the increase in the hours-of-service provision. For example, the reference and simulated load curves of the residential demand component are shown in Figure B.1 - where the green load curve corresponds to the reference of 3 kWh/day-residential for an off-grid user in Colombia (UPME, 2019).

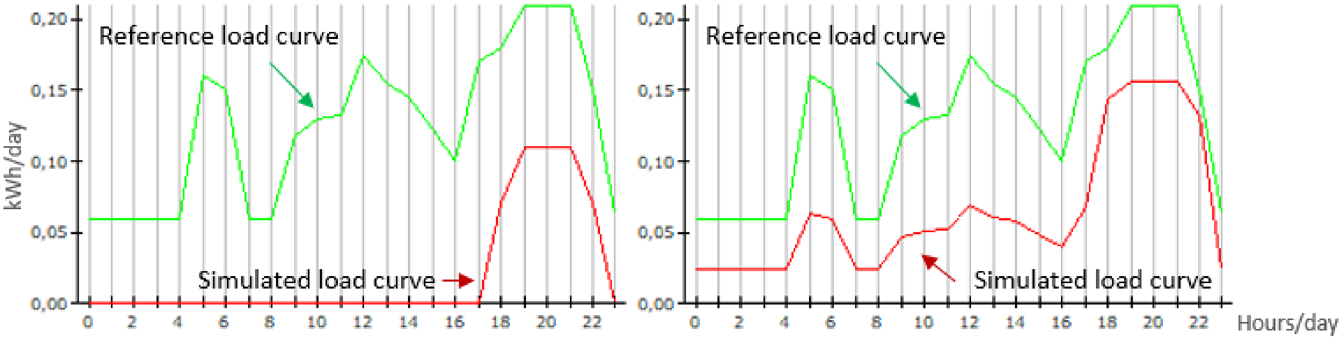


Figure B.1. Reference vs Simulated load curves for the residential demand component. Source: Authors' own.

2. Installed capacity and generation

As shown in Figure B.2, the installed capacity is represented by two levels, one for diesel and one for solar PV; however, other technologies can be incorporated if necessary. It should also be made clear that the model only builds new renewable installed capacity – in this case, solar PV.

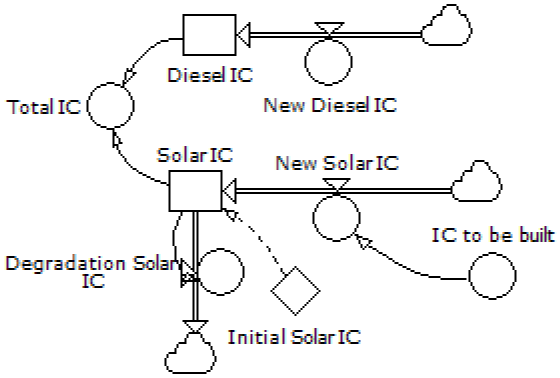


Figure B.2. Installed capacity. Source: Authors' own

System generation is simulated based on the installed capacity, and involves estimating the potential generation of each of the technologies according to the available generation resources. Having estimated the potential generation, the generation is calculated as shown in Figure B.3.

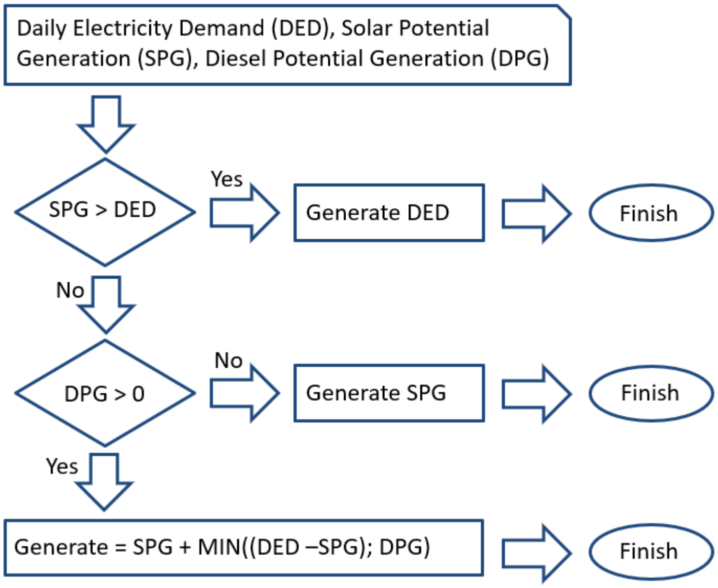


Figure B.3. Dispatch for daily electricity generation. Source: Authors' own.

3. Cash flows and repowering

Cash flows are made up of three main stocks: 1) ESP Financial Resources (FR), 2) FR Repositions and 3) FR CAPEX, where money balances are accumulated in USD (see Figure B.4). The amount of money at each of these levels depends on the inflows and outflows, which represent average annual revenues, savings, and expenditures respectively.

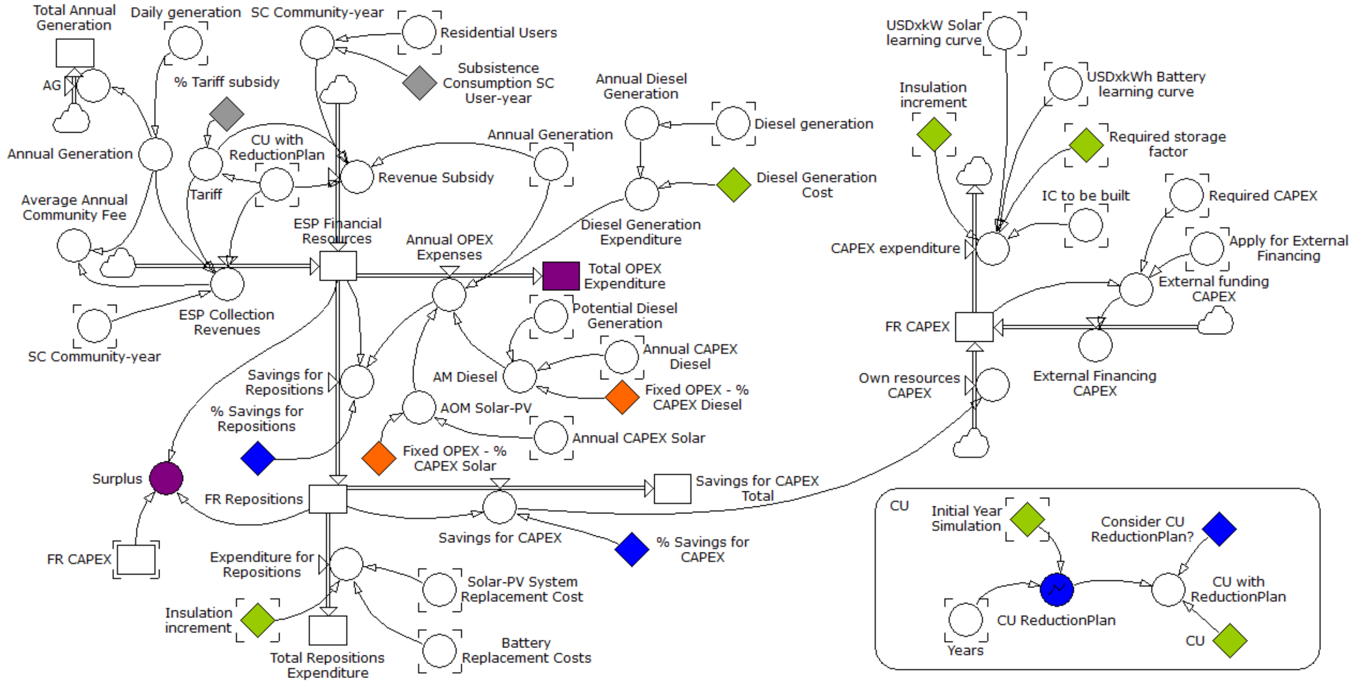


Figure B.4. Stocks and flows diagram of cash flows. Source: Authors' own.

- ESP Financial Resources: This accumulating variable is where the money collected through user charges is deposited, as well as the income from the tariff subsidy in the case that the community has this benefit. In addition to these two inflows, this variable has two outflows - "Annual OPEX Expenses" and "Savings for Repositions", as shown in the following equation:

$$\text{ESP Financial Resources} = 0 + \int_0^t (\text{ESP Collection Revenues} + \text{Revenue Subsidy} - \text{Annual OPEX Expenses} - \text{Savings for Repositions})\, dt$$

- FR Repositions (Financial resources for repositions): "Savings for Repositions" is an outflow for the level variable "ESP Financial Resources", and is the only inflow of the stock FR Repositions. FR Repositions has two outflows corresponding to the expenditures for replenishments and savings for the installation of new installed capacity, as follows:

$$\text{FR Repositions} = 0 + \int_0^t (\text{Savings for Repositions} - \text{Expenditure for Repositions} - \text{Savings for CAPEX})\, dt$$

- FR CAPEX (Financial resources for CAPEX): From this stock comes the money for the repowers, where the inflow "Own resources CAPEX" has the same value as the outflow "Savings for CAPEX" from the stock "FR Repositions". FR CAPEX has two inflows and only one outflow, as shown in the following equation:

$$\text{FR CAPEX} = 0 + \int_0^t (\text{Own resources CAPEX} + \text{External Financing CAPEX} - \text{CAPEX expenditure})\, dt$$

Appendix C

Table C.1 presents the most relevant simulation model parameters.

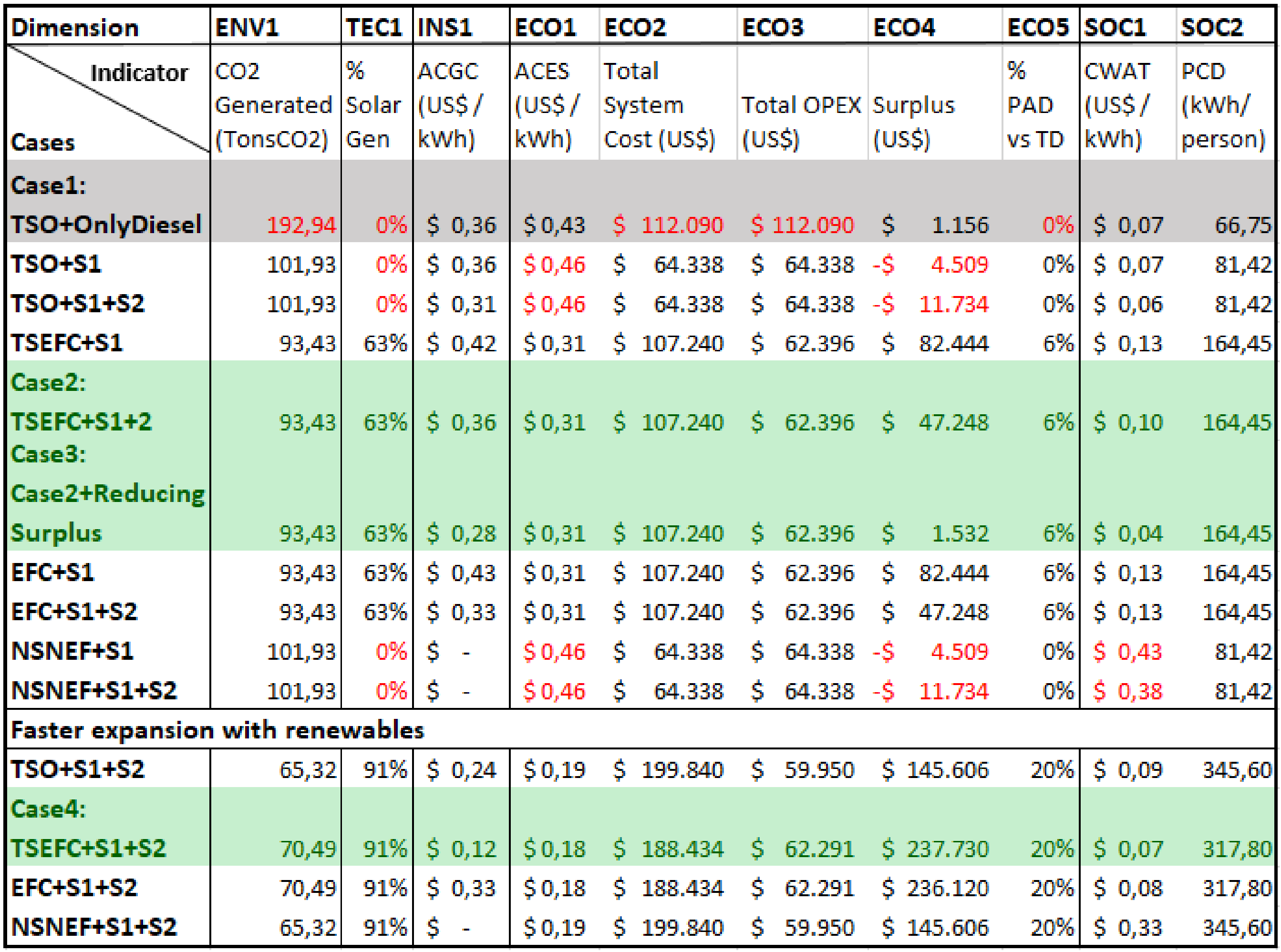
Table C.1. Simulation model parameters

Parameter	**Value and measurement**	**Source**
Diesel Installed Capacity	28 kW	Estimated from SUI (2019a)
Potential diesel generation	42 kWh-day	Estimated from SUI (2019a)
Diesel Decreasing Parameter	5% decrease in initial capacity each year	This value is assumed so that by 2040 the potential diesel generation is 0
PSH - Peak Solar Hours	4.5 hours/day	Estimated from IDEAM (2020)
CAPEX Diesel	650 US$/kW	(Viteri et al., 2019)
Fixed Diesel OPEX – Diesel Generation	3% of CAPEX diesel	Average value is taken from (EU and MWH, 2016, p. 2)
Variable Diesel OPEX	0.38 US$/kWh	Estimated from MME (2019) and SUI (2019b)
Fixed Solar and batteries OPEX	2%	Average value is taken from (EU and MWH, 2016, p. 2)
CAPEX Solar System	1604 US$/kW	(IRENA, 2020)
Calendar Life - PV Solar System	20 years	(Vides-Prado et al., 2018)
Learning curve – Cost Solar System	{0,084; 0,134; 0,184; 0,234; 0,284; 0,333; 0,383; 0,433; 0,483; 0,532; 0,582; 0,632; 0,636; 0,641; 0,645; 0,649; 0,654; 0,658; 0,662; 0,667; 0,671; 0,675}	Estimated from NREL (2020)
Battery costs in US$/kWh	533,62 US$/kWh	Estimated from IRENA (2017b)
Calendar life Lithium-ion Batteries LFP	10 years	Lower value from IRENA (2017b)
Learning curve – Cost Lithium-ion Batteries LFP	{0,067; 0,134; 0,147; 0,165; 0,237; 0,290; 0,339; 0,384; 0,424; 0,460; 0,496; 0,549; 0,589; 0,605; 0,628; 0,643; 0,673; 0,688; 0,711; 0,734; 0,749; 0,764; 0,780}	Estimated from NREL (2020)
Isolated increment	1.7	Highest value from Gaona et al. (2015)
CU (Localities Type 3 and 4)	0.43 US$/kWh	Estimated from SUI (2019b)
% Tariff subsidy (Localities Type 3 and 4)	83%	Estimated from SUI (2019b)

Appendix D

The full simulation results are summarised in Table D.1.

Table D.1. Simulation results



Dimension	ENV1	TEC1	INS1	ECO1	ECO2	ECO3	ECO4	ECO5	SOC1	SOC2
Indicator / **Cases**	CO2 Generated (TonsCO2)	% Solar Gen	ACGC (US$ / kWh)	ACES (US$ / kWh)	Total System Cost (US$)	Total OPEX (US$)	Surplus (US$)	% PAD vs TD	CWAT (US$ / kWh)	PCD (kWh/ person)
Case1: TSO+OnlyDiesel	192,94	0%	$ 0,36	$ 0,43	$ 112.090	$ 112.090	$ 1.156	0%	$ 0,07	66,75
TSO+S1	101,93	0%	$ 0,36	$ 0,46	$ 64.338	$ 64.338	-$ 4.509	0%	$ 0,07	81,42
TSO+S1+S2	101,93	0%	$ 0,31	$ 0,46	$ 64.338	$ 64.338	-$ 11.734	0%	$ 0,06	81,42
TSEFC+S1	93,43	63%	$ 0,42	$ 0,31	$ 107.240	$ 62.396	$ 82.444	6%	$ 0,13	164,45
Case2: TSEFC+S1+2	93,43	63%	$ 0,36	$ 0,31	$ 107.240	$ 62.396	$ 47.248	6%	$ 0,10	164,45
Case3: Case2+Reducing Surplus	93,43	63%	$ 0,28	$ 0,31	$ 107.240	$ 62.396	$ 1.532	6%	$ 0,04	164,45
EFC+S1	93,43	63%	$ 0,43	$ 0,31	$ 107.240	$ 62.396	$ 82.444	6%	$ 0,13	164,45
EFC+S1+S2	93,43	63%	$ 0,33	$ 0,31	$ 107.240	$ 62.396	$ 47.248	6%	$ 0,13	164,45
NSNEF+S1	101,93	0%	$ -	$ 0,46	$ 64.338	$ 64.338	-$ 4.509	0%	$ 0,43	81,42
NSNEF+S1+S2	101,93	0%	$ -	$ 0,46	$ 64.338	$ 64.338	-$ 11.734	0%	$ 0,38	81,42
Faster expansion with renewables										
TSO+S1+S2	65,32	91%	$ 0,24	$ 0,19	$ 199.840	$ 59.950	$ 145.606	20%	$ 0,09	345,60
Case4: TSEFC+S1+S2	70,49	91%	$ 0,12	$ 0,18	$ 188.434	$ 62.291	$ 237.730	20%	$ 0,07	317,80
EFC+S1+S2	70,49	91%	$ 0,33	$ 0,18	$ 188.434	$ 62.291	$ 236.120	20%	$ 0,08	317,80
NSNEF+S1+S2	65,32	91%	$ -	$ 0,19	$ 199.840	$ 59.950	$ 145.606	20%	$ 0,33	345,60

References

Alstone, P., Gershenson, D., Kammen, D.M., 2015. Decentralized energy systems for clean electricity access. Nat. Clim. Chang. 5, 305–314. https://doi.org/10.1038/nclimate2512

Banco de la República, n.d. Tasa Representativa del Mercado (TRM - Peso por dólar) [WWW Document]. URL https://www.banrep.gov.co/es/estadisticas/trm (accessed 6.10.22).

Barlas, Y., 1994. Model Validation in System Dynamics. Proc. 1994 Int. Syst. Dyn. Conf. https://doi.org/10.1002/(SICI)1099-1727(199623)12:3<183::AID-SDR103>3.0.CO;2-4

Bhattacharyya, S., et.al., 2013. Rural Electrification Through Decentralised Off-grid Systems in Developing Countries, Green Energy and Technology. Springer London, London. https://doi.org/10.1007/978-1-4471-4673-5

Boliko, C.M., Ialnazov, D.S., 2019. An assessment of rural electrification projects in Kenya using a sustainability framework. Energy Policy 133. https://doi.org/10.1016/j.enpol.2019.110928

Chaurey, A., Ranganathan, M., Mohanty, P., 2004. Electricity access for geographically disadvantaged rural communities-technology and policy insights. Energy Policy 32, 1693–1705. https://doi.org/10.1016/S0301-4215(03)00160-5

Cherni, J.A., Dyner, I., Henao, F., Jaramillo, P., Smith, R., Font, R.O., 2007. Energy supply for sustainable rural livelihoods. A multi-criteria decision-support system. Energy Policy 35, 1493–1504. https://doi.org/10.1016/j.enpol.2006.03.026

Come Zebra, E.I., van der Windt, H.J., Nhumaio, G., Faaij, A.P.C., 2021. A review of hybrid renewable energy systems in mini-grids for off-grid electrification in developing countries. Renew. Sustain. Energy Rev. 144. https://doi.org/10.1016/j.rser.2021.111036

Congreso de Colombia, 1994. Ley 142 de 1994 - Servicio Públicos Domiciliarios.

Cosenz, F., Noto, G., 2018. A dynamic business modelling approach to design and experiment new business venture strategies. Long Range Plann. 51, 127–140. https://doi.org/10.1016/j.lrp.2017.07.001

Cosenz, F., Rodrigues, V.P., Rosati, F., 2020. Dynamic business modeling for sustainability: Exploring a system dynamics perspective to develop sustainable business models. Bus. Strateg. Environ. 29, 651–664. https://doi.org/10.1002/bse.2395

CREG, 2020. Zonas no Interconectadas | CREG [WWW Document]. URL https://www.creg.gov.co/sectores/energia-electrica/zonas-no-interconectadas (accessed 6.2.20).

CREG, 2007. Resolución CREG 091 de 2007 - Por la cual se establecen las metodologías generales para remunerar las actividades de generación, distribución y comercialización de energía eléctrica, y las fórmulas tarifarias generales para establecer el costo unitario.

Diouf, B., Pode, R., Osei, R., 2013. Initiative for 100% rural electrification in developing countries: Case study of Senegal. Energy Policy 59, 926–930. https://doi.org/10.1016/j.enpol.2013.04.012 Communication

Dyner, I., 2000. Energy modelling platforms for policy and strategy support. J. Oper. Res. Soc. 51, 136–144. https://doi.org/10.1057/palgrave.jors.2600813

Dyner, I., Alvarez, C., Cherni, J., 2005. Energy contribution to sustainable rural livelihoods in developing countries: A system dynamics approach, in: The 23rd International Conference of the System Dynamics Society. Boston.

EU, MWH, 2016. Sustainable Energy Handbook - Module 6.1: Simplified Financial Models.

Franco, C., Dyner, I., Hoyos, S., 2008. Contribución de la energía al desarrollo de comunidades aisladas no interconectadas: un caso de aplicación de la dinámica de sistemas y los medios de vida sostenible en el suroccidente colombiano. Dyna 75, 199–214.

Gaona, E.E., Trujillo, C.L., Guacaneme, J.A., 2015. Rural microgrids and its potential application in Colombia. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2015.04.176

Garces, E., 2021. Alternativas de gestión para el suministro eléctrico sostenible en Zonas No Interconectadas. Universidad Nacional de Colombia.

Garces, E., Tomei, J., Franco, C.J., Dyner, I., 2021. Lessons from last mile electrification in Colombia: Examining the policy framework and outcomes for sustainability. Energy Res. Soc. Sci. 79. https://doi.org/10.1016/j.erss.2021.102156

Greasley, A., Owen, C., 2016. Behavior in models: A framework for representing human behavior, in:

Behavioral Operational Research: Theory, Methodology and Practice. Palgrave Macmillan, pp. 47–63. https://doi.org/10.1057/978-1-137-53551-1_3

Hartvigsson, E., Ehnberg, J., Ahlgren, E.O., Molander, S., 2021. Linking household and productive use of electricity with mini-grid dimensioning and operation. Energy Sustain. Dev. 60, 82–89. https://doi.org/10.1016/j.esd.2020.12.004

Hartvigsson, E., Stadler, M., Cardoso, G., 2018. Rural electrification and capacity expansion with an integrated modeling approach. Renew. Energy 115, 509–520. https://doi.org/10.1016/j.renene.2017.08.049

Henao, F., Cherni, J.A., Jaramillo, P., Dyner, I., 2012. A multicriteria approach to sustainable energy supply for the rural poor. Eur. J. Oper. Res. 218, 801–809. https://doi.org/10.1016/j.ejor.2011.11.033

Huneke, F., Henkel, J., Benavides González, J.A., Erdmann, G., 2012. Optimisation of hybrid off-grid energy systems by linear programming. Energy. Sustain. Soc. 2, 7. https://doi.org/10.1186/2192-0567-2-7

IDEAM, 2020. Atlas de Radiación Solar, Ultravioleta y Ozono de Colombia [WWW Document]. URL http://atlas.ideam.gov.co/visorAtlasRadiacion.html (accessed 4.5.20).

IEA, 2021. World Energy Outlook 2021, IEA. Paris.

IEA, 2017. Energy Access Outlook 2017: From poverty to prosperity. https://doi.org/10.1787/9789264285569-en

IEA, IRENA, UNSD, World Bank, WHO, 2020. Tracking SDG7: The Energy Progress Report. Washington, D.C.

IPSE, CNM, 2021. Informe mensual de localidades sin telemetria de las ZNI. Bogotá D.C. – Colombia.

IRENA, 2021. The Renewable Energy Transition in Africa: Powering Access, Resilience and Prosperity.

IRENA, 2020. Renewable Power Generation Costs in 2019. Abu Dhabi.

IRENA, 2019. Off-grid renewable energy solutions to expand electricity access: An opportunity not to be missed.

IRENA, 2017a. Accelerating Off-grid Renewable Energy: Key Findings and Recommendations from IOREC 2016. Iorec,2016 1–24. https://doi.org/978-92-95111-07-3

IRENA, 2017b. Electricity storage and renewables: Costs and markets to 2030. Abu Dhabi.

Jimenez, M., Cadavid, L., Franco, C.J., 2014. Scenarios of photovoltaic grid parity in Colombia. Dyna 81, 237–245. https://doi.org/10.15446/dyna.v81n188.42165

Jimenez, R., 2017. Barriers to electrification in Latin America: Income, location, and economic development. Energy Strateg. Rev. 15, 9–18. https://doi.org/10.1016/j.esr.2016.11.001

Kanagawa, M., Nakata, T., 2008. Assessment of access to electricity and the socio-economic impacts in rural areas of developing countries. Energy Policy 36, 2016–2029. https://doi.org/10.1016/j.enpol.2008.01.041

Krithika, P.R., Palit, D., 2013. Participatory Business Models for Off-Grid Electrification, in: Bhattacharyya, S. (Ed.), Rural Electrification Through Decentralised Off-Grid Systems in Developing Countries. Springer, pp. 187–225.

Kumar, A., Mohanty, P., Palit, D., Chaurey, A., 2009. Approach for standardization of off-grid electrification projects. Renew. Sustain. Energy Rev. 13, 1946–1956. https://doi.org/10.1016/j.rser.2009.03.008

Kunc, M., Mortenson, M.J., Vidgen, R., 2018. A computational literature review of the field of System Dynamics from 1974 to 2017. J. Simul. 12, 115–127. https://doi.org/10.1080/17477778.2018.1468950

Mandelli, S., Barbieri, J., Mereu, R., Colombo, E., 2016. Off-grid systems for rural electrification in developing countries: Definitions, classification and a comprehensive literature review. Renew. Sustain. Energy Rev. 58, 1621–1646. https://doi.org/10.1016/j.rser.2015.12.338

MME, 2020. Fondo De Solidaridad Para Subsidios y Redistribución de Ingreso - FSSRI [WWW Document]. URL https://www.minenergia.gov.co/fssri1 (accessed 11.23.20).

MME, 2019. Resolucion MME 412113 de 2019.

MME, 2007. Resolución 182138 de 2007 - Por la cual se expide el procedimiento para otorgar subsidios del sector eléctrico en las Zonas No Interconectadas.

Nabavi, E., Daniell, K.A., Najafi, H., 2017. Boundary matters: the potential of system dynamics to support sustainability? J. Clean. Prod. 140, 312–323. https://doi.org/10.1016/j.jclepro.2016.03.032

Narula, S.A., Bhattacharyya, S., 2017. Off-grid electricity interventions for cleaner livelihoods: A case study of value chain development in Dhenkanal district of Odisha. J. Clean. Prod. 142, 191–202. https://doi.org/10.1016/j.jclepro.2016.07.176

NREL, 2020. Electricity Annual Technology Baseline (ATB) [WWW Document]. URL https://atb.nrel.gov/electricity/2020/data.php (accessed 11.23.20).

Ortiz-Jara, R.P., Pérez-Arriaga, J.I., Dueñas, P., González, A., Eslava Mejia, M., Juan Revolo, M., 2020. Misión de Transformación Energética y Modernización de la Industria Eléctrica: Hoja de Ruta para la Energía del Futuro - Foco No. 4. Cierre de brechas, mejora de la calidad y diseño y formulación eficiente de subsidios.

Presidencia de la República, 2001. Decreto 2884 de 2001, por el cual se reglamenta el Fondo de Apoyo Financiero para la Energización de las Zonas no Interconectadas -FAZNI-. Bogotá.

Rahman, M.M., Paatero, J. V., Lahdelma, R., 2013. Evaluation of choices for sustainable rural electrification in developing countries: A multicriteria approach. Energy Policy 59, 589–599. https://doi.org/10.1016/j.enpol.2013.04.017

Riva, F., Ahlborg, H., Hartvigsson, E., Pachauri, S., Colombo, E., 2018. Electricity access and rural development: Review of complex socio-economic dynamics and causal diagrams for more appropriate energy modelling. Energy Sustain. Dev. 43, 203–223. https://doi.org/10.1016/j.esd.2018.02.003

Riva, F., Colombo, E., 2020. System-dynamics modelling of the electricity-development nexus in rural electrification based on a Tanzanian case study. Energy Sustain. Dev. 56, 128–143. https://doi.org/10.1016/j.esd.2020.04.001

Riva, F., Colombo, E., Piccardi, C., 2019. Towards modelling diffusion mechanisms for sustainable off-grid electricity planning. Energy Sustain. Dev. 52, 11–25. https://doi.org/10.1016/j.esd.2019.06.005

Rocha, H., Kunc, M., Audretsch, D.B., 2020. Clusters, economic performance, and social cohesion: a system dynamics approach. Reg. Stud. 54, 1098–1111. https://doi.org/10.1080/00343404.2019.1668550

Silva, D., Nakata, T., 2009. Multi-objective assessment of rural electrification in remote areas with poverty considerations. Energy Policy 37, 3096–3108. https://doi.org/10.1016/j.enpol.2009.03.060

SSPD, 2021. Zonas No Internonectadas - Informe Sectorial De La Prestación Del Servicio De Energía Eléctrica 2021. Bogotá D.C. – Colombia.

SSPD, 2020. Zonas No Internonectadas - Informe Sectorial De La Prestación Del Servicio De Energía Eléctrica 2020. Bogotá D.C. – Colombia.

SSPD, 2019. Zonas No Interconectadas - ZNI: Diagnóstico de la Prestación del Servicio de Energía Eléctrica 2019, Superintendencia de Servicios Públicos Domiciliarios - SSPD. Bogotá.

SSPD, 2018. Zonas No Interconectadas - ZNI: Diagnóstico de la Prestación del Servicio de Energía Eléctrica 2018. Bogotá.

Sterman, J., 2000. Business dynamics: systems thinking and modeling for a complex world, Irwin/McGr. ed, Irwin/McGraw-Hill. Jeffrey J. Shelsfud, Boston. https://doi.org/10.1108/13673270210417646

SUI, 2019a. Compra de combustible y aspectos de generación. Bogotá D.C. – Colombia.

SUI, 2019b. Formato ZNI C1 - Información Comercial para el Sector Residencial. Bogotá D.C. – Colombia.

Terrado, E., Cabraal, A., Mukherjee, I., 2008. Designing Sustainable Off-Grid Rural Electrification Projects: Principles and Practices. Washington, D.C. https://doi.org/10.1596/1813-9450-5193

Tomei, J., Cronin, J., Arias, H.D.A., Machado, S.C., Palacios, M.F.M., Ortiz, Y.M.T., Cuesta, Y.E.B., Lemus, R.P., López, W.M., Anandarajah, G., 2020. Forgotten spaces: How reliability, affordability and engagement shape the outcomes of last-mile electrification in Chocó, Colombia. Energy Res. Soc. Sci. 59. https://doi.org/10.1016/j.erss.2019.101302

Torres, J.P., Kunc, M., O'Brien, F., 2017. Supporting strategy using system dynamics. Eur. J. Oper. Res. 260, 1081–1094. https://doi.org/10.1016/J.EJOR.2017.01.018

UPME, 2019. Plan Indicativo de Expansión de Cobertura de Energía Eléctrica PIEC 2019-2023, UPME.

Vides-Prado, A., Camargo, E.O., Vides-Prado, C., Orozco, I.H., Chenlo, F., Candelo, J.E., Sarmiento, A.B., 2018. Techno-economic feasibility analysis of photovoltaic systems in remote areas for indigenous communities in the Colombian Guajira. Renew. Sustain. Energy Rev. 82, 4245–4255. https://doi.org/10.1016/j.rser.2017.05.101

Viteri, J.P., Henao, F., Cherni, J., Dyner, I., 2019. Optimizing the insertion of renewable energy in the off-grid regions of Colombia. J. Clean. Prod. 235, 535–548. https://doi.org/10.1016/j.jclepro.2019.06.327