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Assessing the Impact of Applying Individual Discount Rates in Power System Expansion of Ecuador Using OSeMOSYS

Roberto David Heredia Fonseca[a]*, Francesco Gardumi[a]

[a] *Department of Energy Technology - Energy Systems, KTH Royal Institute of Technology, Brinellvägen 68, 10044 Stockholm, Sweden.*

ABSTRACT

The development of the electricity supply sector needs data and energy system models to aid government instances to achieve optimal decision-making. Since 2006, Ecuador has faced gradual changes in the electricity sector and invested more than 11 billion dollars in expanding the generation. We use an open-source model generator in the present study and develop the first long-term generation expansion model for Ecuador. We select specific social and hurdle rates to represent the government's decision to mobilize private energy infrastructure investments. We build scenarios for social and hurdle rates to evaluate the sensitivity of renewable and conventional generation technologies to such rates. Results show that medium and large hydropower have a low sensitivity to discount rates. Medium and large hydropower plays a significant role in the energy mix in the mid and long-term, regardless of the discount rate. Results from this model find no significant contribution of non-hydro renewables. Among these, only geothermal reaches around 160 MW for all scenarios. Installing geothermal and hydropower minimizes generation from conventional technologies until 2034; then, CCGT installations increase CO2 emissions above 2020 levels.

Keywords

Open-source;
Generation;
Social discount rates;
Hurdle rates;
OSeMOSYS;

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1. Introduction

In the last decade, Ecuador has undergone significant energy infrastructure decisions, particularly in the power sector. The power sector has faced significant improvements from the enhancement of the service quality and decrease in energy losses to substantial investment in infrastructure, to name a few. Investment in the power sector reached more than $11 billion from 2007 to 2016. Notably, the government mainly invested in renewables with particular attention to hydropower and thermal power plants fueled by domestic production of fossil fuels such as oil products and natural gas. As a result, the country doubled the installed electricity generation capacity that it had before 2006 and achieved more than 99% access to electricity in 2018 [1,2].

In 2018, the total installed capacity reached approximately 7.2 GW, and around 70% is hydropower (Table 1. Installed power supply capacity in 2018 in Ecuador.). A key aspect of such investments in the power sector is the government's alignment to the Agenda 2030, the sustainable development goals (SDGs), and SDG #7 [3]. According to the government, in the long-term, the power sector's enhancement would be primarily based on renewables rather than conventional technologies, and it would be funded by investments from the private sector [4,5]. The total capacity used in this work did not include self-generating capacity for 2018. Nominal self–generating capacity was around 1.6 GW, and only around 168.9 MW were available for the public, as seen in Table 6, in Appendix 1.

*Corresponding author – e-mail: rdhf@kth.se

Table 1: Installed power supply capacity in 2018 in Ecuador.

Type	Power plant	Nominal Capacity (MW)	Effective Capacity (MW)	%[4]
Renewables	Hydro	5050.5	4970.6	70.6
	Wind	16.5	16.5	0.2
	Solar PV[1]	24.5	23.6	0.3
	Bio-gas	7.3	6.5	0.1
Non-renewable	ICE[2]	786.1	680.4	11.0
	Combustion turbine[3]	820.6	698.6	11.5
	Thermal-steam	446.0	418.0	6.2
	Total 1	*7151.5*		
Self-generation	Thermal, hydro	1494.2	1180.8	
	Biomass	144.3	135.4	
	Total 2	*1638.5*		
	Total 1 + total 2	*8.7 [GW]*		

[1]Solar photovoltaic. [2]Internal combustion engine. [3]Includes single cycle gas turbine (SCGT). [4]Based on Total 1

However, the fact that Ecuador's government is considering investments from the private sector raises uncertainty and risk. Public investment is the investment by a state in particular assets, for instance, generation technologies. Public investments account for a global discount, the social discount rate (SDR). Contrary to public investment, private investment has individual discount rates or hurdle rates (HR) for every single generation technology. In other words, HR is the expected return from an investor perspective.

Generation technologies usually have a long useful lifetime (e.g., hydropower, thermal power plants). Electricity generation projects face costs at different times during the useful life, i.e., during the evaluation process, at the construction phase, during operation, and in the decommissioning phase. Since such time span is so large, it is crucial to select the proper discount rate when a government or private investor is likely to invest in a long lifetime and high capital-intensive energy projects.

In this regard, only a few studies in the literature, for instance, Garcia-Gusano et. al. [6] and Hermelink et. al. [7], have analyzed social and hurdle rates and their effect on energy models outputs. The former discusses findings in modeling assumptions as inputs in the PRIMES [6] energy system model. The main findings suggest that higher discount rates make less attractive high-energy efficiency investments. The authors found differences between the discount rates used by member states and those applied in the European Commission (EU) impact assessments. The latter, in turn, the authors modified the inputs for hurdle and social discount rates and analyzed the outputs of two well-known models, ETSAP-TIAM [7] and TIMES-Norway [8]. This study showed that changes in both social and hurdle rates affect the energy system, i.e., the lower the SDR, the higher the renewable contribution. While these studies focus on the European region, a literature review did not show similar analyses in the Latin American Region (LAC). As such, the first and primary objective of the present paper is to investigate the sensitivity of the results from a capacity expansion model to different SDR and HR due to the lack of studies in the LAC region.

Secondly, to test the sensibility of the model outputs, we first develop an open-source energy system optimization model for Ecuador. This model determines different future investments in conventional and renewable generation technologies and provides a view of the potential role of each of these technologies in the electricity mix. With the aid of this open-source model and open energy data, we support the transparency and reproducibility of energy systems models. The present paper builds on the data from governmental agencies. The energy system model is developed by using the open-source energy model generator OSeMOSYS [9].

In the following section, we describe the structure of the model, the underlying assumptions, and the scenarios developed for this study. Section 3 shows the results and scenario comparison, including the sensitivity to both SDR and HR. Relevant results and policy implications are discussed in Section 4. Finally, concluding remarks of this study are made in Section 5.

2. Materials and Methods

In this section, we give a brief description of the modeling tool selected for this study. We show the Reference Energy System (RES) that represents the model we developed, including resources and existing and future generation technologies. These future generation technologies include renewable potentials, as shown in Table 2. Additionally, we include the underpinning assumptions related to demand projections, renewable targets, and energy efficiency policies that the country aims to achieve. We give a brief explanation of how the individual discount rate is incorporated into the modeling tool and a short literature review related to discount rates. Finally, the scenario definitions are shown in Section 2.3

2.1. Model structure

This study traces the development of the open-source, long-term energy system model for Ecuador. With the aid of the open-source model generator OSeMOSYS, we investigate the sensitivity of generation technologies to SDR and HR.

The power sector development needs data and energy system models to aid government instances to achieve optimal decision-making. To date, there are a number of well-known and established long-term energy system modeling frameworks [6,7,10], such as MARKAL/TIMES, MESSAGE, and PRIMES that have served as tools to analyze long-term energy policies and strategies according to [11,12]. Some of these models have become free for academic purposes or completely available as an open-source under GNU general public license, as seen in [12]. However, these frameworks often require a valid commercial license for user interface (UI) and solvers for the optimization process.

Unlike models described earlier, a fully open-source model generator such as OSeMOSYS does not require an upfront cost [9]. Zero cost means its user interface (UI) and model are freely available. Several studies [13–15] have used OSeMOSYS to develop local and regional applications and upscaled globally. Furthermore, studies have shown that this tool can replicate results from other renowned models, as seen in [16,17].

OSeMOSYS minimizes the total system cost for a given available and mix of technologies. In doing so, the optimization process meets energy demands and complies with several exogenous constraints in the analysis period. Such constraints account for the availability of resources (e.g., oil, gas, coal) and performance and costs for different conversion technologies (e.g., gas power plants, hydropower plants, solar PV), domestic and import energy resources such as fuel prices for electricity generation.

The Reference Energy System (RES) is a graphic abstraction that represents the model that we developed. In this graphic representation, lines symbolize energy carriers. They are connected to blocks representing conversion processes or energy services. RES illustrates the conversion chains from energy resources on the left to generation, transmission and distribution, and final energy demands on the right. Figure 1 presents the RES for Ecuador and provides a breakdown of resources, technologies, and energy carriers. The period within which the modeling occurs is from 2018 to 2050. Further key techno-economic assumptions, fuel prices, and future investments in generation are presented in

Table 2: Renewable energy potential in Ecuador.

Resource	Potential			Source
Hydropower	Large scale	> 50 MW	10903.9 MW	[23]
	Medium scale	10-49 MW	1215.2 MW	
	Small scale	1-9 MW	200.8 MW	
Geothermal			554 MW	[1]
Wind			475 MW	[24]
Biomass[1]			500 MW	[25]
Solar[2]			2543 $Wh.m^{-2}.day^{-1}$	[26]

[1] Potential calculated by taking advantage of 50% of biomass residues. [2] Average solar direct insolation

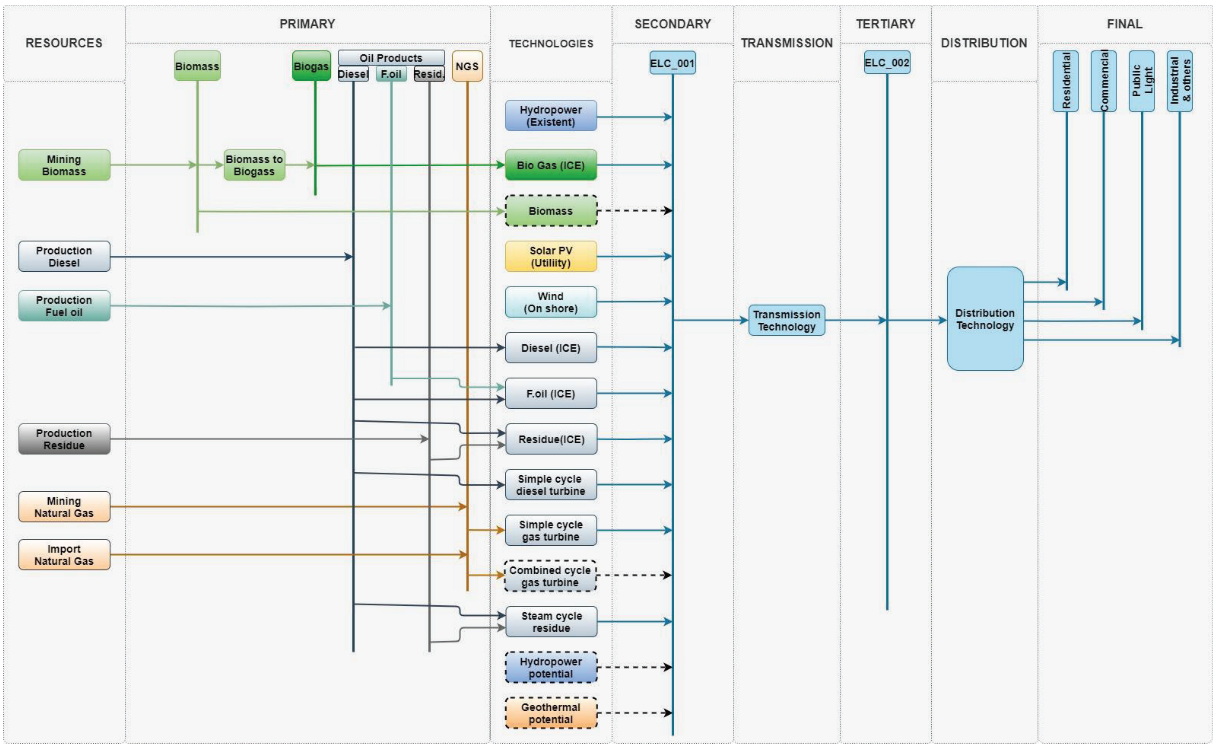

Figure 1: Simplified Reference Energy System of the Ecuador power sector.

Appendix 2; a supplementary webpage developed for this paper, as seen in [18].

Concerning resources, Ecuador produces crude oil-focused on exports but also for its own consumption. The country produces oil products such as fuel oil, residue, diesel, and natural gas fueling thermal power plants. In this study, we disaggregated thermal power plants by technology and fuel (e.g., internal combustion engines, steam turbine), hydropower potential by size (large, medium, small), and the potential for non –hydro renewables (e.g., geothermal, wind, solar). In this model, we used the effective capacity as inputs for the existing capacity. According to the Ministry of Energy, the geothermal potential is around 900 MWe. However, in this study, we use a more conservative value based on several studies that have examined the geothermal potential, as seen in [19,20]. In the last years, as seen in [21], capacity factors for an existent wind farm have increased from 41 to 63 % and 98% for availability. Instead, in this model, wind potential has a conservative value based on wind speed higher than 7.5 ms^{-1} and 25% capacity factor. Table 2 shows the renewable energy potential for Ecuador. This information is open for public use and was taken from several public institutions [22].

We also considered all existing and the most recent power generation installations. The residual capacity and recent installations allowed the country to increase its total installed capacity to approximately 7.3 GW. This model further considers future new potential installations, as seen in Table A3, in Appendix 2, a supplementary webpage developed for this paper [18].

2.1.1. Demand projections

In the last decade, different electricity demand forecasts have been proposed to illustrate how the demand will change in the coming years. These demand forecasts were the result of either statistical evaluations or projections from former consumption trends. Also, such projections were developed by government agencies, as shown in [27], in collaboration with external institutions, as noted in [28], or by individual studies, as seen in [29].

In the Ecuadorian model, we use demand projections from the Electrification Master Plan 2016-2025 [1]. This electrification plan was the latest study developed by multiple institutions, including the Ministry of Energy, Ecuador’s regulatory agencies, and supported by the Inter-American Development Bank (IDB). The methodology used for developing demand projections considered technical and economic variables such as GDP, population, household number, and size. Additionally, it also considered four different electricity consumption sectors: residential, commercial, industrial, and public lighting. We accounted for an average demand growth (see in Figure A 2a- Appendix 1) and individual load curves (see in Figure A 2b- Appendix 1) for each of these four sectors.

Ecuador experiences a dry and rainy season in a year. The dry season tends to occur from October to March, while the country has a rainy season from April to September. As such, the electricity supply varies according to those seasons. For instance, thermal power plants usually generate more electricity during the dryer season than in rainy seasons. This variation in the generation is because most hydropower facilities are located in the eastern basin of the country, including Paute-Mazar, one of the largest reservoirs. The dry season negatively affects hydropower plants by reducing river flows; thus, decreasing generation.

We divided a year into several time slices to capture the variability of renewable resources and demand variations. To define the time slices, we used and explored the time series every 30 minutes of demand in 2018, as seen in Figure 2 [30]. We use boxplots to identify the high peaks by month and time of demand, as seen in Figure A 1a and Figure A 1b in Appendix 1. Twelve seasons were identified, one per month, given the dissimilarities of average demand per month. Additionally, a day was subdivided into six different periods and different lengths to capture significant demand variations. One single day type was select for the model. Therefore, in the model for Ecuador, we used 72-time slices.

2.1.2. Renewable targets and energy efficiency

Ecuador does not undertake legally binding emissions reduction targets due to being a non –annex I country of The United Nations Framework Convention on Climate Change (UNFCCC). However, the country voluntarily self-imposed a target to reach at least 60% of renewable generation capacity by 2017 [31].

In recent years, the national development plan for the period between 2017 and 2021 [3] stated that the Ecuadorian government's goal was to increase from 60 to 90% of electricity generation from renewables by 2021. Increasing generation from renewables follows Ecuador's nationally determined contributions (NDC) [32]. NDC includes an energy efficiency plan (PLANEE), efficient cocking (nation-wide adoption of electric cookstoves), and the development of hydropower and non-hydro renewables, including biogas from landfills. Other relevant energy efficiency goals adopted by the government are shown in Table 3.

PLANEE is seen as a public policy instrument. Its goal is to promote a culture of energy efficiency based on disseminating success cases and recognizing good practices in all demand sectors. As such, the government,

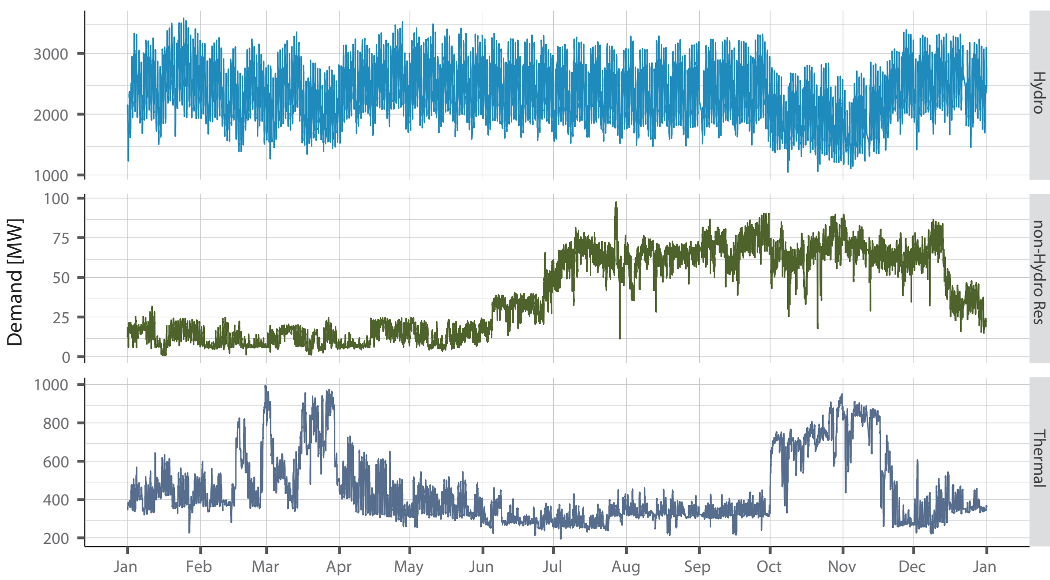

Figure 2: Electricity demand in 2018. Non-hydro renewables include solar, wind, biomass, and biogas.

Table 3: Energy efficiency goals

Goal	Description	Source
Renova plan:	Upgrading old inefficient for new high efficient appliances for the residential sector.	[33]
ISO 50001	Implementing energy management systems for the demand sector.	
Distribution losses.	Reduction from ~12 to 8%	[1]
Renewables	Decrease the use of fossil fuels electricity generation	

by implementing energy efficiency policies, will contribute to achieving sustainable development goals (SDG) and specifically SDG 7. Increasing the rate of energy efficiency by 2030 is one of the targets in SDG 7 and the Sustainable Energy for All initiative (SE4ALL).

2.2. Discount rates in OSeMOSYS

The OSeMOSYS model is written in blocks of equations that compute energy balances, capacity and activity constraints, and costs. All costs are summed up into a system cost minimized over the entire model period in the objective function. The total cost includes fixed and variable costs, capital investment, emission penalty, and salvage value by technology each year. In OSeMOSYS GNU MathProg, the discount rate is a function of the region (r), as seen in equation Eq. (1).

param DiscountRate{r in REGION}; (1)

Being an open-source energy modeling system allows the modeler to update the model in specific parameters to meet individual necessities. For instance, in this model, we apply different discount rates for each technology. As such, the discount rate can be defined as a function of a technology (t) in a region (r) Eq. (2).

param DiscountRateIdv{r in REGION, t in TECHNOLOGY}, default DiscountRate[r]; (2)

This update in the OSeMOSYS model allows the modeler to use a global discount or SDR as input for Eq. (1) and the specific HR as inputs for Eq. (2). We modified in the OSeMOSYS code the instances involving both DiscountRate, and DiscountRateIdv. In addition, we implemented a new parameter PvAnnuity which allows the calculation of the present value of the investment cost for each of the technologies when using specific discount rates. This new definition is deemed as an important contribution to the tool itself, with potential applicability beyond the electricity and energy sectors. As such, the modeler can set individual discount rates for each technology. The code implementation used for this study is further elaborated in Appendix 2, a supplementary webpage developed for this paper [18]; additionally, it is hosted in a public repository [34].

2.3. Scenario definitions.

In this study, we first defined a baseline, a business as usual scenario (BAU). This scenario accounts for existent, committed, and under construction hydro and thermal power facilities. For example, committed infrastructure includes 14.6 MW, 254.4 MW, and 593 MW hydropower plants. Additionally, the model accounts for a combined cycle gas turbine (CCGT) of 110 MW). This scenario is set free to optimize future installations after the installation of committed infrastructure, and it does not include any energy efficiency targets.

Regarding fuels, we assumed no future investment to increase natural gas production and distribution for electricity generation in the BAU scenario, currently decreasing from around 10.5 PJ per year, as seen in [35]. However, the other set of scenarios exhibit an opposite effect for natural gas, assuming investments to keep the current natural gas production as shown in [36]. All scenarios have the possibility to use imported natural gas for generation.

Additionally, all scenarios account for committed and future planned power generation infrastructure that the Ecuadorian government is likely to invest in. As a key assumption in this model, future generation infrastructure will follow the schedule proposed by the government, as shown in Table A 3 in Appendix 2 [18]. Except for the BAU scenario, the other scenarios are combined with different SDR and HR to define individual scenarios, as shown in Table 4. These scenarios include energy efficiency on the demand side, as described in section 2.1.2. Additionally, each scenario is allowed to install new capacity within the potential for hydropower and non-hydro renewables, as seen in Table 2.

In OSeMOSYS, a global discount rate is used to discount the total system cost for a given mix of technologies under several exogenous constraints. The total system cost includes operating cost, investment cost, emission penalties, and salvage value. However, when using specific discount rates-hurdle rates for each individual technology, the individual discount rate is used to

Table 4: Scenarios definition for Ecuador's model.

Sets	Scenario	Discount rate [%]	Hurdle rates[3]	Facilities			Natural gas	Energy Efficiency demand[1]
				existent	Under construction	Expansion Plan[2]		
Social discount rates	BAU_75[a]	7.5	-	✓	✓			
	SC_75	7.5	-	✓	✓	✓	✓	✓
	SC_10	10.0	-	✓	✓	✓	✓	✓
	SC_12	12.0	-	✓	✓	✓	✓	✓
Hurdle rates	LHR	10.0	Low HR[5]	✓	✓	✓	✓	✓
	HHR	10.0	High HR[5]	✓	✓	✓	✓	✓

Note. All scenarios account for the existent capacity and decommissioning of power plants. [1]BAU- Business as usual does not include energy efficiency on the demand side and transmission-distribution lossless (PLANEE). [b]future planned generation facilities (see in Table A3, Appendix 2). [3]Low and high hurdle rates, as seen in Table 5.

calculate a series of equal payments, from the Capital Investment, spread over the operational life of generation technology. Then, the individual payments are discounted to the model base year by the global discount rate.

In the Ecuadorian model, a 7.5% social discount rate is considered as a baseline. This discount rate is an optimistic assumption for a country in South America. There is only one piece of evidence from country to regional studies that establish such a discount factor for non-OECD countries as a reference [37]. In addition, two social discount rates of 10 and 12% are used in the model to define new scenarios for analysis; these are set as mid and upper bounds, respectively. Several researchers [38–40] have studied how social discount rates vary in developing economies. These studies show that International Multi-lateral Development Banks often apply discount rates from 10 to 12% to developing countries. A more specific study by Moore et al. [41] states similar values for discount rates for several South American countries, except for Ecuador, ranging from 10 to 12%. Only Chile accounts for the lowest value of six percent in South America.

Further, a power systems interconnection in South American based on the SAMBA model developed by Pinto de Moura et al. [14] assumes a global discount rate of 8%. Notably, only one specific hydropower project in Ecuador shows the discount rate at 10% as a reference [42]. The Secretary for Planning in Ecuador suggests using a social discount rate of 12% as a reference value for Latin American countries (LAC) (e-mail to Secretary of Planning, June 15, 2020; unreferenced). In this study, we use three social discount rates of 7.5, 10, and 12%.

This study also includes specific discount rates or hurdle rates for different technologies on the supply side. The purpose of using technology-specific hurdle rates (HR) is to note the sensitivity in the whole system when installing specific technologies. Because of the lack of data for the LAC region, we use hurdle rates developed by the Committee on Climate Change and the Department of Energy and Climate Change [43,44]. These reports used an extended capital asset pricing model (CAPM) for determining hurdle rates. The hurdle rates are consistent with data obtained by Estache et al. [45]. This study reveals an average cost of capital for the LAC region of 12%, specifically for upper-middle-income countries such as Ecuador [46]. Additionally, it suggests the cost of capital from 10 to 11% in the energy sector. Since literature advises low and high hurdle rates, two scenarios were drawn using such values, as seen in Table 5.

3. Results and discussion

To test the sensitivity of several electricity generation technologies to SDR and HR, we developed six scenarios in an open-source energy modeling system. Interestingly, there is one significant finding when considering committed and future planned energy infrastructure by the government. Installations of large hydropower, geothermal, and CCGT power plants from 2022 to 2027 make future installations decline in the period between 2028 and 2035, as seen in Figure 3.

In general, reducing distribution losses and improving grid efficiency make new capacity installations lower for SDR and HR scenarios than the base scenario

Table 5: Hurdle rates for different technologies in the Ecuadorian model.

Technology	LHR (%)	HHR (%)	Source
Geothermal	8.9	12.1	
Steam turbine (oil products)	8.3	11.5	[43]
Internal combustion engine/reciprocating	8.0	11.2	
Hydro large scale	6.8	10.0	
Hydro medium scale	6.8	10.0	[43,47]
Hydro small scale	6.8	10.0	
Biogas	7.0	10.0	
Biomass	9.0	13.0	
Solar Photovoltaic	6.0	9.0	
Wind onshore	7.0	10.0	[44]
Combustion turbine	6.0	9.0	
Single-cycle gas turbine	6.0	9.0	
Natural gas combined cycle	6.0	9.0	

BAU_75. New capacity decreases from 12.9 GW in the BAU_75 scenario to an average of 11.5 GW for SDR, HR scenarios. As a result, future investments make new capacity lower by around 1.4 GW for SDR and LHR scenarios; however, the LHR scenario exhibits an opposite effect (see Figure 3). LHR scenario accounts for the higher installed new capacity of 11.9 GW due to the higher deployment of large-scale hydro. Large-scale hydro reaches 6.3 GW for the LHR scenario. The following subsections present selected results for specific technologies in the model.

3.1. Large and medium scale hydro

Large-scale hydropower stands out as the technology for a large deployment for all SDR and HR scenarios. There is no marked difference in the size of installations for new large (Hydro_L) and medium (Hydro_M) scale hydropower as the SDR increases. Large-scale hydropower shows low sensitivity to SDR; this technology reaches an average of 5.8 GW. Similarly, large-scale hydropower varies by about 0.5 GW or around $96 million, in 2018 money, for HR scenarios and reaches around 6.3 GW for the LHR scenario.

Medium-scale hydropower appears to be little sensitive to discount rates. There is no variation in the total installed capacity for this technology, reaching 0.98 GW in 2050 for BAU and HR scenarios (see Figure 5). This constant capacity can be attributed to a higher cost-competitiveness of medium-scale hydropower than other technologies, related to upfront costs, construction period, and low operational costs. However, this

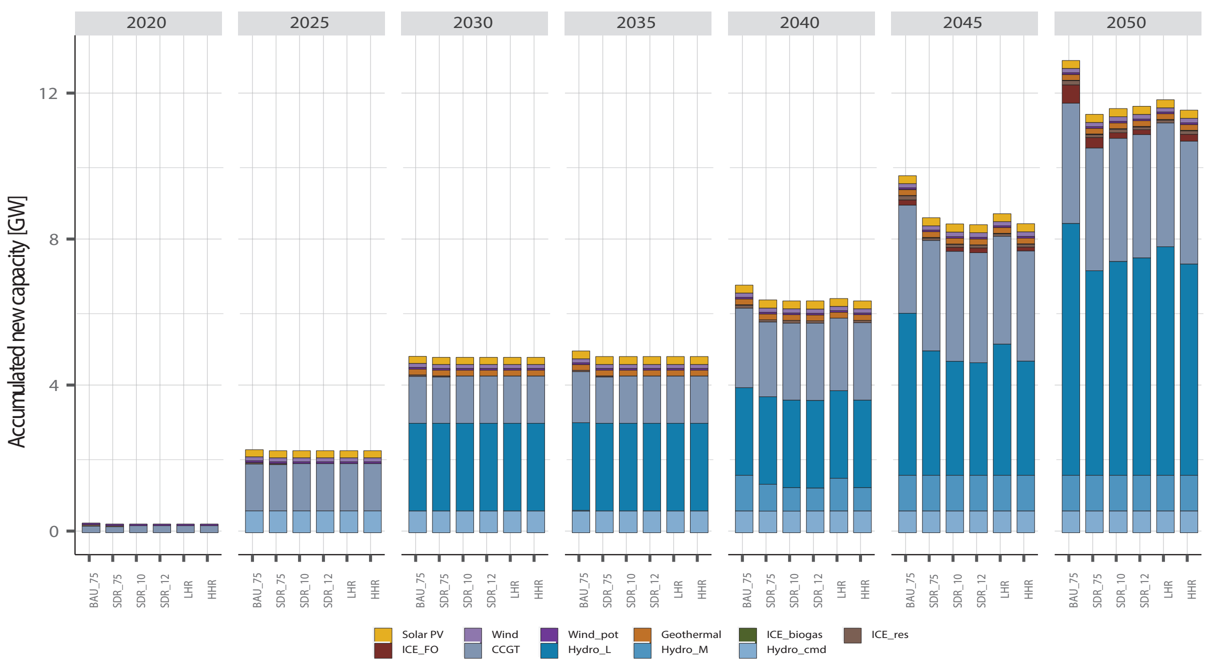

Figure 3: Accumulated new capacity [GW] for BAU, SDR, and HR scenarios

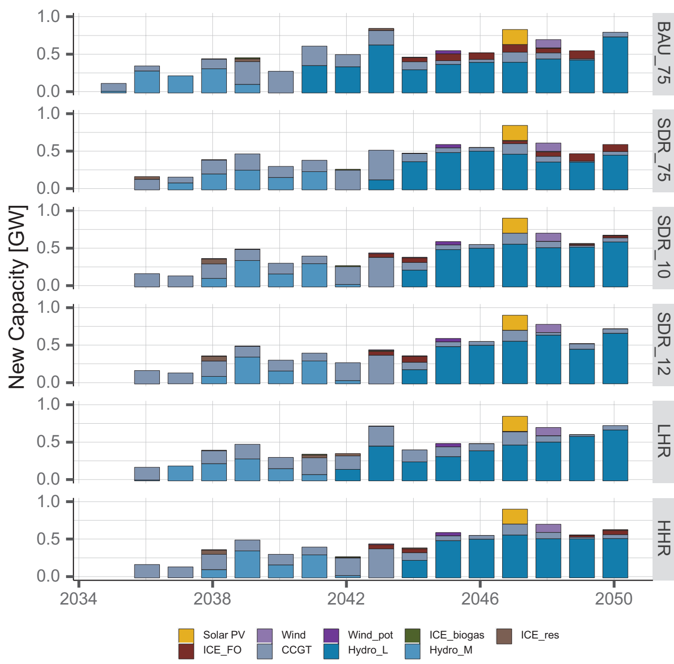

Figure 4: New Capacity [GW] for BAU, SDR, and HR scenarios from 2035 to 2050

technology does not reach its full potential, which is more than 1.2 GW.

Figure 4 shows installed new capacity from 2035 to 2050 for all scenarios. This figure makes it possible to appreciate the low sensitivity of medium and large hydropower to SDR and HR. A variation in the discount rate makes few differences in hydropower installations. For instance, new medium and large hydropower installations start in 2038 and 2044 for scenarios SDR_12 and HHR, respectively. Decreasing the discount rate, as in scenarios SDR_75 and LHR, in turn, makes the investments in hydropower occur from one to two years earlier. A variation in the discount rate shows no effect on wind and solar PV generators, as discussed in Section 3.2.

In general, findings in this study indicate similarities to those developed by Pinto de Moura et al. [14] and Inter-American Developed Bank [48] regarding the increasing generation from hydropower. These similarities imply that Ecuador will continue relying on hydropower generation in the mid and long term. However, contrary to the former studies, this study uses different discount rates to explore the sensitivity of generation technologies. This high dependency on hydropower can be attributed to lower operation costs. Hydropower projects, once these are commissioned, need low maintenance during operation; thus, they have low variable costs. The Ecuadorian government used to set a variable cost for hydropower generation, which was used not only in the dispatch but also in other transactions. This cost reached values as low as 2 USD/MWh, as seen in [49].

Concerning discount rates for hydropower, the rate increases or is adjusted to reflect risk mainly in the development and construction stages. A low discount rate from 6.8 to 7.5% used in this study is related to low-risk technology, given that hydropower is a mature technology. Nonetheless, a higher discount rate; for example, 12%, reflects risk and a significant uncertainty level given three specific reasons. First, private investors can have several risk interpretations; therefore, they can have differences in their rate of return. As a result, private investors may require a higher return (risk premium) to compensate them for the risk. Second, we assume both social discount rates and hurdle rates with no variation over the model period in this model. The latter is not entirely correct because there is less confidence in the likely future estimates for these rates, as suggested in [43]. For instance, the rate of return is considered speculative and high during the feasibility study in the development stage of any renewable project. Later, in the operation stage, this discount rate becomes real and conservative [50]. Third, studies developed in the early 2000s [51] suggested that climate change would affect the financial performance of hydropower. In Ecuador, however, there is a high level of uncertainty regarding climate change. Studies [52,53] suggest that climate change would affect river flows and negatively affect hydropower generation. On the contrary, a vulnerability assessment of water resources developed in Ecuador in 2008 [54] showed no conclusive results given the lack or incomplete time series of hydro-meteorological data.

3.2. Non-hydro renewables installations

Non-hydro renewables, such as solar PV, biomass, geothermal, are part of the mix for SDR and HR scenarios, but at a lower scale. Results show that modifying SDR and HR did not have a noticeable effect on the new installed capacity for these technologies. Wind, solar, and biogas accounted for around 160 MW, 221 MW, and 20 MW at the end of the modeled period, respectively. New investments in these technologies only take place to replace old installations after these have reached their lifetime. Consequently, non-hydro renewables represent only three to four percent of the total installed capacity in the country (see Figure 5).

3.2.1. Solar PV

The lack of new solar PV installations seems to stem from low incentives. No policies support solar PV or incentive to install solar applications despite the country's sizeable solar potential, as seen in Table 2. Ecuador used to have one Feed-in Tariff (FIT) scheme for solar installations until 2011 [55]. Such regulation was updated in 2014 and excluded incentives for solar PV and wind power [56]. In 2016, FIT schemes were derogated, given the new law of electricity for public service and promoting a new scheme based on credits for grid-connected PV systems [57]. The lack of incentives is one aspect that needs further development and assessment to ensure penetration of solar PV installation in the future. A study developed by Jacobs et al. [58] identified several issues related to LAC region policies with limited renewable energy deployment. The study showed that not well-designed FIT policies, political and regulatory risk were the leading causes of market constraint for renewables and specifically solar PV. Further assessments are needed combining falling electricity costs for solar PV and different discount rates. The latter can aid in developing or redesigning low-risk policies that can attract new investments [59].

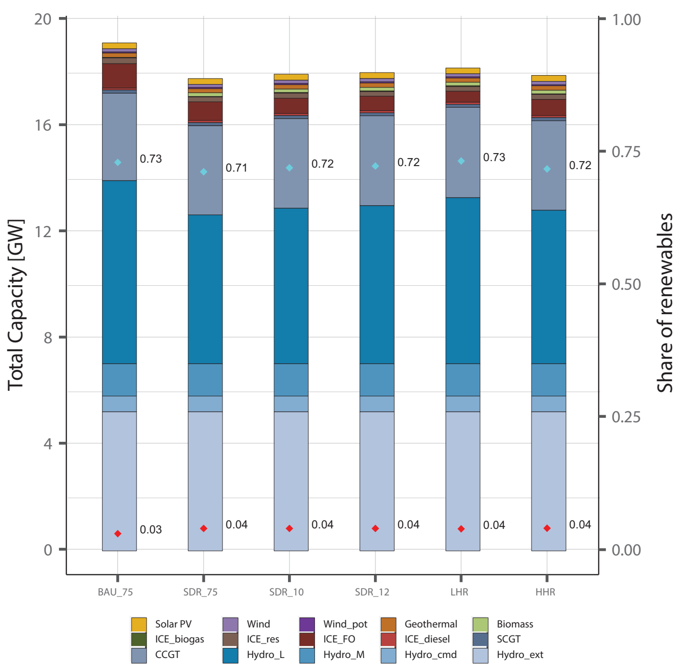

Figure 5: Total capacity [GW] for BAU, SDR, and HR scenarios in 2050 (left axis). Share of renewables installations (right axis). Red and cyan marks represent the share of non-hydro renewables and hydro capacity, respectively.

3.2.2. Biomass
Another technology not considered in the mix of technologies is biomass. The result shows that only a specific application would contribute to the future by generating electricity, which is waste-to-energy (WtE). This technology is currently in the country, and it is fueled by bagasse from sugar cane plantations. Other plug&play technologies fueled by biogas from the anaerobic digestion of the poultry industry are also present in the country but at a lower scale [60]. According to the atlas of bioenergy for Ecuador, the country accounts for large quantities of biomass. Several studies [61,62] have contributed to the analysis and development of biomass as an energy source. However, only a single study showed biomass as a promising feasible solution not for electricity generation but in biofuels production, as see in [63].

3.2.3. Geothermal
Even thought, as seen in [64], geothermal becomes more cost-competitive at higher than 80% of capacity factor and at higher fossil fuel prices, for example, imported natural gas, this was not the case in this model. Geothermal power did not stand out in both sets of scenarios due to its high capital investment. Geothermal reached a limited deployment of around 160 MW for all scenarios, as seen in Figure 3. Regarding discount rates, these are considered high for geothermal, given the risks associated with the development stage. The limited access to the resource, often remote, increases the risk of developing geothermal energy and its commercial development [65]. As such, geothermal needs incentives from the public sector and Clean Development Mechanisms (CDM) to be economically competitive, as suggested in [66].

3.3. Fossil fuel power plants
CCGT is predominant among several other thermal generation technologies for all SDR scenarios. Large-scale hydropower has a higher cost-competitiveness than CCGT. The new installed capacity for CCGT does not face a significand change reaching on average around 3.3 GW, for SDR and LHR and HHR scenarios (see Figure 3 and Figure 5). In HR scenarios, higher discount rates did not benefit less capital-intensive technologies, such as CCGT, which offers a shorter construction period from one to two years, and lower capital costs. As a result, approximately more than 70% of the total installed capacity is dominated by hydropower, reaching 80% for the HHR scenario. CCGT loses competitiveness when considering this type of generation fueled by a mix of local and imported natural gas at higher prices. Ecuador would import natural gas to secure supply for generation, industry, and residential sectors in about 50 MMCF, given the depletion of local resources [67].

On the other hand, thermal technologies fueled by oil products are affected by different hurdle rates. Scenarios LHR and HHR show a marked increase in new installations for generators fueled by local oil products. Conventional generators reach from 0.95 GW to 1.2 GW for HHR and LHR, respectively.

3.4. Electricity generation mix
The evolution of the generation mix in the study period is another aspect highlighted (see Figure 6). Comparing SDR and HR scenarios, these show a significant contribution of hydropower. The country will achieve more than 90% of electricity generation from renewables in the short and mid-term; however, it would fail in the long term. On the other hand, increasing the SDR decreases the fraction of generation by renewables from higher than 0.90 to 0.84. This change in the fraction is because at higher SDR, the investments for CCGT increase. There is no noticeable change in the fraction by renewables in LHR and HHR scenarios regardless of the hurdle rate.

3.5. Emissions of $CO_{2\text{-eq}}$
When accounting for planned infrastructure by the government, results show a steady decline in emissions from 3000 kT of $CO_{2\text{-eq}}$ to 250 kT by 2027, as shown in Figure 7. Even though results show significant investments in hydropower and geothermal, these do not ensure low emissions levels after 2027. In fact, there is a steady increase in emissions to 2018 levels, which reach 3 million tons of $CO_{2\text{-eq}}$ by 2035 due to early CCGT installations for SDR and HR scenarios. Emissions can reach between 5 to 6 million tons of $CO_{2\text{-eq}}$ by 2050 for SDR and HR scenarios. This increase in emissions is due to investments in non-gas thermal power plants (e.g., oil products) affected by the low and high hurdle rates.

The findings in this study are subject to three limitations. First, techno-economic assumptions adopted in this model are set to have no variation over time. These assumptions include costs, fuel prices, and technology cost projections, to name a few. The no variation over time of these assumptions is considered acceptable if the

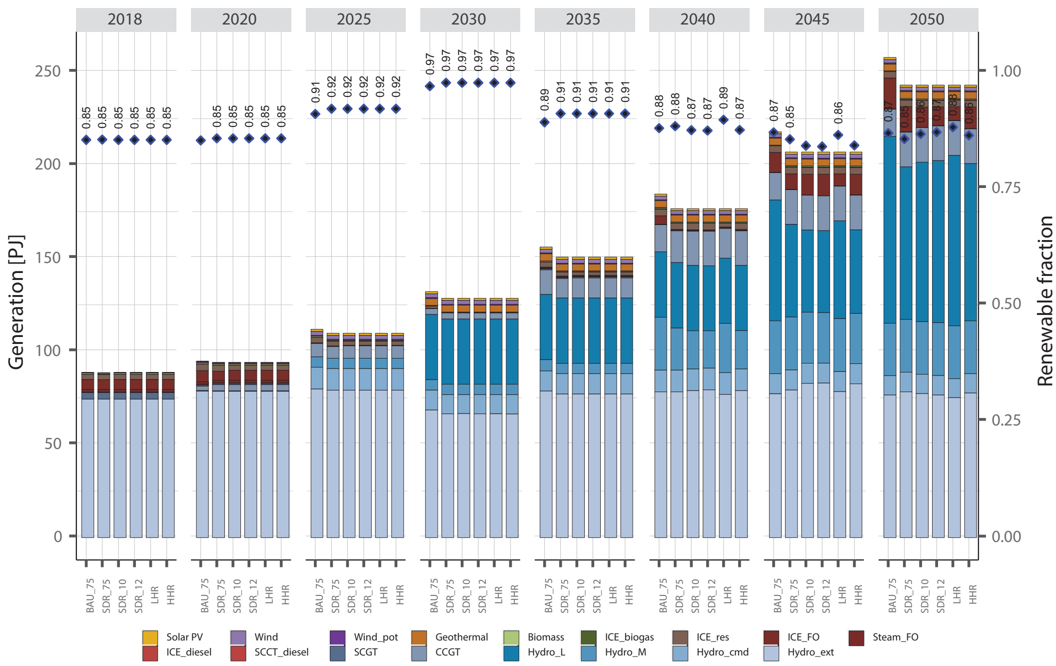

Figure 6: Electricity generation mix (left) and renewables fraction (right) for BAU, SDR, and HR scenarios

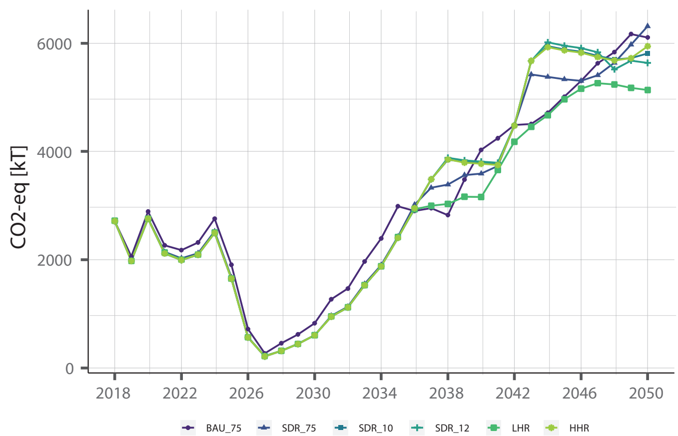

Figure 7: Emissions per year for BAU, SDR, and HR scenarios.

purpose is to compare scenarios by modifying the discount rates. However, more research is needed, analyzing the impact of variations in fuel prices and the declining costs for non-hydro renewables, for instance, through a sensitivity analysis or stochastic program. These analyses can help to understand and, to some extent, quantify the implications of the uncertainty surrounding these parameters on the generation expansion plan. Second, this study does not consider the socioeconomic and environmental impacts of the future expansion plan and impacts of climate change on generation. These impacts, in turn, may have significant effects on the development of the power system, especially in large hydropower projects. Climate change and the frequency of severe events could put at risk hydropower facilities and alter the cost of capital for future investments. Third, hurdle rates as the cost of capital can vary over time, not considered in the present model. This variation in hurdle rates is due to the CAPM model; the risk premium and beta can vary over time depending on a specific country and investor.

3.6. Policy implications

The growing electricity demand across the LAC region is one of the main factors that have attracted the development of renewable energy policies. These policies include renewable energy laws and renewable energy targets (RET), and regulatory instruments such as auctions, feed-in tariff (FIT), net metering and self-supply, fiscal incentives, and grid access [68]. Across the LAC region, governments and policymakers are making efforts to consider intermittent renewables into the power sector, as seen in [69–71].

In the case of Ecuador's model, results show that hydropower is the selected technology for generation in the country, under a cost-minimization perspective and not considering climate uncertainty. New installations in hydropower can reach an average of 6 GW by 2050. On the other hand, non-hydro res produces only a fraction of the total from renewables. This limited fraction would justify the interest of national policymakers in hydropower as a source of baseload generation in the long term. Other considerations are that large and medium hydropower projects provide additional benefits than generating electricity, such as flood control and firm water supply. Nevertheless, if the government aims to fund future medium and large hydro projects by private utilities, in that case, they will have to deal with contentious social and environmental constraints [72]. Previous developments in the country had faced similar issues and shown how national policymakers and politics played an important role in designing such projects. [73,74].

Regarding energy policy for renewables, Ecuador had a RET. The main objective of this target was to increase electricity generation from renewables from 60 to 90% and decrease the use of imported liquid fuels for generation by 2021. However, this target did not have any disaggregation regarding specific contributions by different renewable technologies. In our model, we did not use any RET to limit the installation of conventional technologies; yet, we include future non-hydro investments. This lack of a specific RET is one of the triggers that makes hydropower the most common installed technology. According to IRENA [68], a specific RET, which included non-hydro renewables, is stated only in two countries across the LAC region; this is the case of Mexico and El Salvador. Mexico RET includes specific hydropower, wind, geothermal, bioenergy, and solar fractions.

Auction is one of the most common regulatory instruments in the LAC region. Auction is a bidding procurement process for electricity from renewables. Often, a long-term contract, a Power Purchase Agreement (PPA), is signed after procurement. In the last years, Ecuador has made available only two non-hydro-res projects for auction. These projects consist of a 258 MW solar PV and 110 MW wind, and the concession of the infrastructure lasts 20 and 25 years, respectively. Other countries in the LAC, such as Argentina, Chile, Mexico, and Brazil, are leading auctions, including non-hydro renewables. These auctions showed clear and defined transition targets and regulatory instruments to support the development of renewables in such countries, as seen in [75–77].

Feed-in tariff and net metering, and self-supply are other instruments used to support the deployment of renewables. However, as discussed in Section 3.2.1, Ecuador has no feed-in tariff schemes anymore. On the contrary, there is no statement regarding net metering and self-supply in the country. Still, self-generation capacity in the country is about 1.6 GW, and only around 10% is available to the public, as seen in Table 6, in Appendix 1. In the last five years, only small biomass (144 MW) and hydropower plants produced a surplus; thus, these were able to feed electricity to the grid [22].

With respect to geothermal, Moya et al. [66]found that one of the main barriers for Ecuador to implement such technology is the lack of one specific geothermal law. In addition to this specific public policy, clean funding mechanisms and public incentives are necessary to make new non-hydro renewables financially and economically feasible.

As such, new discussions regarding renewable energy policies and techno-economic assessment of non-hydro renewables should be done in the country in partnership with nongovernmental organizations and agencies that can help promote the diversification of renewable sources, for example, as seen in [78].

4. Conclusions

To meet future demand, significant investments in energy infrastructure are necessary and imminent in Ecuador. This study sets out to develop the first long-term open-source energy system model to provide a foundation for Ecuador to analyze long-term investment scenarios. The scenario comparison analysis illustrates that renewable technologies significantly contribute in the mid and long-term, and hydropower stands out in the generation mix. Hydropower contributes in around 70% in SDR and LHR scenarios of total installed capacity. It reaches 80% in the HHR scenario. The share of renewables in generation exceeds 90% in the short and mid-terms but decreases in the long run.

Unlike the substantial contribution of hydropower, other technologies such as solar PV and onshore wind participate in the generation mix but at a lower scale. As such, further research is required in low-risk policies that can potentially attract investment and increase the influence of non-hydro renewables. Similarly, geothermal is shown to have a limited deployment in the country in scenarios accounting for government plans and hurdle rates, as seen in Figure 3. The deployment of geothermal happens after 2026, at a fraction of its full potential of around 554 MW. Geothermal can become a cost and environmentally feasible option to conventional generation by incorporating financial incentives and Clean Development Mechanism (CDM).

In this paper, we have examined the impact of applying SDR rates into the model. The results provide evidence of the high importance of SDR in evaluating long-term energy infrastructure, and these are considered one of the most critical drivers in any analysis. Specifically, this is the first study to make available evidence for the sensitivity of SDR and HR for generation technologies in Ecuador. Considering both SDR and HR, results reveal that the country would continue relaying in large hydropower in the mid and long terms. Unfortunately, no studies have been developed in the LAC region to determine hurdle rates specifically for the energy sector. We applied hurdle rates from well-renowned institutions in this paper. Finally, hurdle rates from the private sector remain uncertain in the LAC region and often unavailable for researchers; we identified this limited access of such rates as a gap for future assessment.

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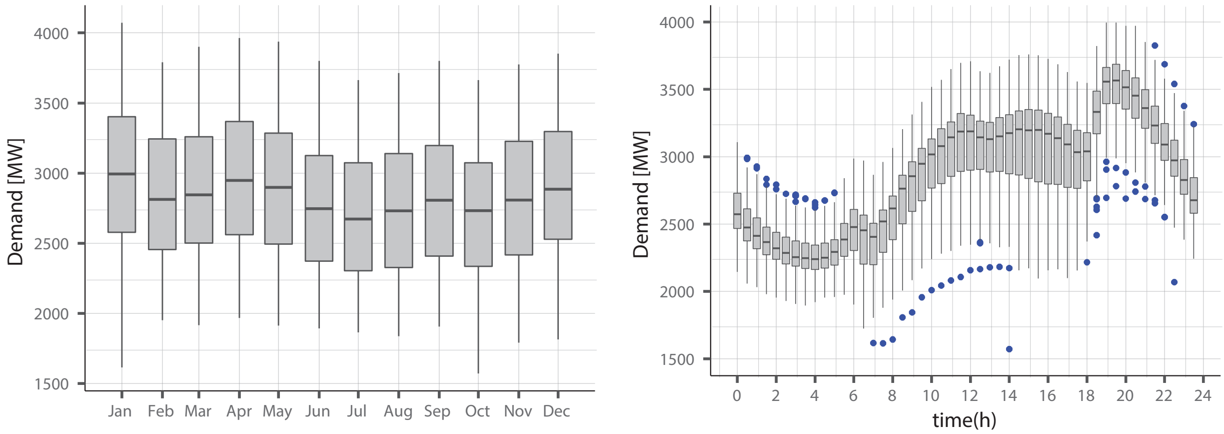
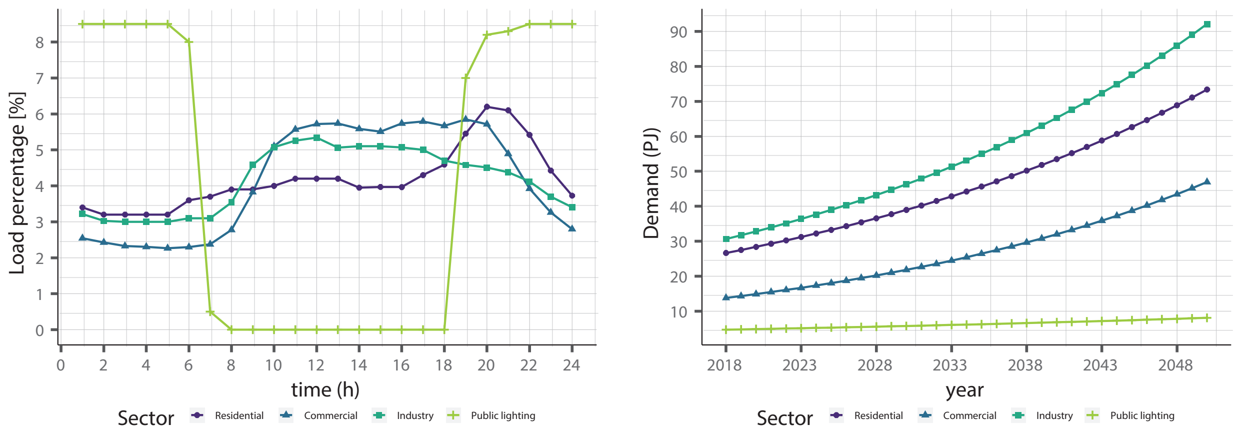
Appendix 1: Average demand in 2018, load curves by sector, and demand projections for Ecuadors' model.



(a) (b)

Figure A 1: Average demand in 2018. (a) By month (b) by time.



(a) (b)

Figure A 2: (a) Load curves by sector. The public lighting load curve presents an instant demand at sunset, following zero demand at sunrise. Adapted from [5,79]. (b) Demand projections.

Table 6: Self-generation capacity in 2018

Capacity (MW)					
Public		No Public		Total	
Nominal	Real	Nominal	Real	Nominal	Real
168.9	165.4	1469.6	1151.8	1638.5[1]	1317.2

[1]Includes biomass (bagasse) power plants, based on [22]