Challenges for hydropower-based Nationally Determined Contributions: A case study of Ecuador

Abstract

Hydropower is the dominant renewable energy source to date, providing over two-thirds of all renewable electricity globally. For countries with significant hydropower potential, the technology is expected to play a major role in the energy transition needed to meet nationally determined contributions (NDCs) for greenhouse gas (GHG) emission reductions as laid out in the Paris Agreement. For the Republic of Ecuador, large hydropower is currently considered as the main means for attaining energy security, reducing electricity prices and mitigating GHG emissions in the long-term. However, uncertainty around the impacts of climate change, investment cost overruns and restrictions to untapped resources may challenge the future deployment of hydropower and consequently impact decarbonisation efforts for Ecuador's power sector. To address these questions, a partial equilibrium energy system optimisation model for Ecuador (TIMES-EC) is used to simulate alternative electricity capacity expansion scenarios up to 2050. Results show that the share of total electricity supplied by hydropower in Ecuador might vary significantly between 53% to 81% by 2050. Restricting large hydropower due to social-environmental constraints can cause a fourfold increase in cumulative emissions compared to NDC implied levels, while a 25% reduction of hydropower availability due to climate change would cause cumulative emissions to double. In comparison, a more diversified power system (although more expensive) which limits the share of large hydropower and natural gas in favour of other renewables could achieve the expected NDC emission levels. These insights underscore the critical importance of undertaking detailed whole energy system analyses to assess the long-term challenges for hydropower deployment and the trade-offs among power system configuration, system costs and expected GHG emissions in hydropower-dependent countries, states and territories.

Key policy insights

- Ecuador's hydropower-based NDC is highly vulnerable to the occurrence of a dry climate scenario and restrictions to deployment of large hydropower in the Amazon region.
- Given Ecuador's seasonal runoff pattern, fossil-fuel or renewable thermoelectric backup will always be required, whatever the amount of hydropower installed.
- Ecuador's NDC target for the power sector is achievable without the deployment of large hydropower infrastructure, through a more diversified portfolio with non-hydro renewables.

Keywords: Hydropower, NDC, Ecuador, energy modelling, renewable energy

1. Introduction

1.1. Hydropower and Ecuador's NDC

Hydropower is the world's largest single source of renewable electricity, producing around 17% of the world's total electricity and two-thirds of all renewable electricity generation (IEA, 2018). Hydropower's commercial maturity and reliable energy production makes it an attractive alternative to fossil fuel-based technologies, and an important complement to increasing shares of intermittent sources such as wind and solar photovoltaics. For countries with significant hydropower potential, the technology is expected to play a major role in the energy transition needed to meet nationally determined contributions (NDCs) for greenhouse gas (GHG) emission reductions as set out in the 2015 Paris Agreement (UNFCCC, 2015). It has been estimated that if existing global hydropower had been replaced with burning coal, approximately 4 billion tonnes of additional GHGs would have been emitted in 2017 and emissions would have been at least 10% higher (IHA, 2018). However, while hydropower can help mitigate GHG emissions, the technology faces a number of uncertainties (such as generation variability due to climate change, capital cost overruns and social-political opposition) that challenge its future deployment and its integrated role in the power sector and the overall energy system.

In this study, we provide an assessment of hydropower's long-term role in the power system and its contribution towards NDC target compliance. We develop a case study for the Republic of Ecuador, a country that currently relies heavily on hydropower. Between 2007 and 2015, the country invested close to US$6 billion in eight 'flagship' hydropower projects (Gallagher & Myers, 2015) to more than double its hydropower capacity (see Fig. 1) (MEER, 2017). According to the International Hydropower Association (IHA), the country ranked third after only China and Brazil for countries that added new capacity in 2016 (IHA, 2017). This has resulted in Ecuador becoming one of the countries that most rely on hydropower generation in South America — in 2018 over 80% of electricity was generated with hydropower (ARCONEL, 2018). This ambitious deployment of hydropower infrastructure also constitutes part of Ecuador's National Climate Change Strategy (MAE, 2012a, 2017; MAE et al., 2015). Ecuador's GHG inventory showed that Ecuador's energy sector and power sector, accounted for 44% and 15% of total net emissions, respectively (MAE, 2012b). As stated in the National Energy Agenda 2016-2040 (MICSE, 2016a), the Ecuadorian Government's policy is to continue developing large hydropower in the long-term and, although not having any legally binding commitments, it has now established hydropower development as the pillar of its first submitted NDC, which in its ambitious conditional target suggests installing an additional 3.6 GW of new capacity by 2025 (the Santiago-G8 project) (CELEC, 2017; UNFCCC, 2019) (see Fig. 1).

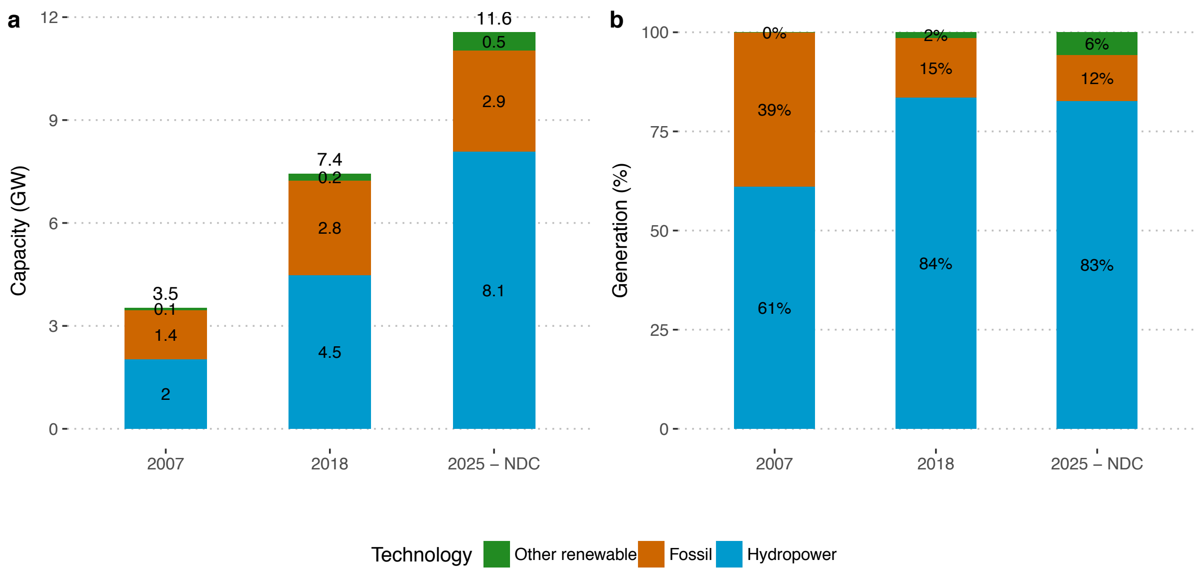

Figure 1. (a) Electricity installed capacity and (b) generation shares in Ecuador according to the conditional NDC and the Electricity Master Plan 2016-2025.

1.2. Critical challenges for hydropower development

The technical, economic and socio-political feasibility of hydropower in long-term energy transitions is subject to several key challenges. For country-scale analyses of hydropower deployment, these are: i) the impact of climate change on the available runoff for hydropower generation; ii) the recurring uncertainty[1] of investment costs associated with hydropower infrastructure; and iii) the effective remaining potential of hydropower resources that can be tapped in the midst of opposition to hydropower projects due to socio-environmental concerns or due to the lack of finance for large hydropower projects. Their criticality is discussed below.

Climate change impact assessment studies have shown that there are considerable discrepancies around the impacts that climate change will have on the magnitude and direction of precipitation and other hydroclimatic variables in the long-term (Cisneros et al., 2014; van Vliet et al., 2016). Different climate projections show that both wetter and drier future climates could be equiprobable, which translates into uncertainty about the availability of hydropower generation. This in addition to current variable inter and intra-annual runoff patterns, which is already a challenge for river water management. Historically, Ecuador has faced electricity crises due to low river flows (electricity rationing in 1996, 2005, 2006, 2009). Between late 2009 and early 2010, the country registered the lowest river flows in the last 46 years, which coupled with some structural problems of the power system, led the country to an electricity crisis that caused several blackouts (Schaeffer et al., 2013) and corresponding economic losses. These cyclical droughts could be exacerbated in intensity and frequency with the impact of climate change.

An additional challenge for hydropower is the risk of capital cost overruns, particularly in large-scale projects (Ansar et al., 2014; Bacon & Besant-Jones, 1998; Callegari et al., 2018). Given that geotechnical conditions cannot be precisely assessed until after the construction of the project begins, hydropower presents inherent difficulties during the construction phase including unforeseen excavations and construction problems that can increase investment requirements considerably. Hydropower has been identified as one of the technologies with the largest average cost overruns (second only to nuclear power), having an average cost overrun of 70%, compared to, for example, a 12% average cost overrun for traditional thermal plants (Sovacool et al., 2014). Ecuadorian hydropower infrastructure during the last decade has also experienced cost overruns. The cumulative cost of the flagship hydropower projects with a total cumulative capacity of 2,832 MW, has had a cost overrun of US$ 1,520 million – a 26% increase when compared to the cumulative initial budget of US$ 5,850 million (Villavicencio, 2015).

Finally, hydropower's further deployment still faces regulatory, financial and social acceptance issues (Winemiller et al., 2016). Hydropower can add to the stress on water resources by contributing to environmental impacts related to the impoundment of water, and the hydrological changes brought about by the construction of dams and the flooding of land upstream (Anderson et al., 2018). Social impacts are also concerns, especially in hydropower projects that require the possible relocation of communities and other species, cross-border international agreements and the competing demands between energy, water and land use (WEC, 2015). These issues can complicate the deployment of future projects and reduce the effective estimated potential of untapped hydropower resources (Gernaat et al., 2017). The most recent hydropower station in Ecuador, Coca Codo Sinclair (1.5 GW), though currently the largest in terms of installed capacity, has itself been constructed with only a small storage reservoir due to environmental concerns in a sensitive area for biodiversity in the Amazon (Escribano, 2013).

2. Materials and methods

2.1. The TIMES-EC model and the representation of hydropower

The Ecuadorian energy system has been modelled with the TIMES (The Integrated MARKAL-EFOM System) energy system optimisation model generator, which is a widely used bottom-up partial equilibrium optimisation modelling platform developed as part of the International Energy Agency – Energy Technology Systems Analysis Program (IEA-ETSAP) (Loulou & Labriet, 2008). The TIMES model applied to the Ecuadorian energy system (TIMES-EC) minimises the total discounted costs of deploying technologies required to cover energy service demands over a multi-decadal time horizon and across multiple diurnal and seasonal time periods. By using an energy system optimisation model, this study assesses the future challenges for hydropower deployment under different scenario assumptions and compares their impacts side by side. Moreover, by using a model of the whole energy system (i.e. going beyond just electricity generation), it is able to explore broader implications for costs, emissions and final energy demand; which is a step forward from existing studies that consider the challenges for hydropower's role in the future independently or only in the context of power generation (Parkinson et al., 2016; Spalding-Fecher et al., 2017; van der Zwaan et al., 2018). Hydropower has been characterised in greater detail by representing: i) the existing and remaining potential at the basin level; ii) the specific technology type and the associated inter-annual power dispatch availability; and iii) the discrete investment characteristics of possible new hydropower projects. Further details on the structure and assumptions of the TIMES-EC model can be found in the Supplemental Material and in Carvajal et al., (2019).

Total hydropower potential in Ecuador adds up to 22.1 GW (ARCONEL, 2015),[2] which is distributed across six large river basins within two regions (Pacific and Amazon), the latter being delimited by the Andes mountains (Fig. 2,a). Different seasonal runoff patterns characterise each of the regions (Fig. 2,b). The remaining techno-economic hydropower potential[3] for new capacity expansion in Ecuador (totalling 13 GW) has been categorised in the model according to the inventory of projects in each basin (ARCONEL, 2015) and three representative capacity sizes: large, medium and small (see Fig 1,c). Based on these assessments Ecuador has great potential mostly for large hydropower projects (9756 MW), followed by medium (2327 MW) and small-sized projects (918 MW). Two types of hydropower technology have been depicted: run-of-river (ROR) and reservoir-based (DAM). The different operational logic of these technologies has been modelled with different types of availability factor attributes[4] that TIMES-EC offers to further specify energy dispatch within the model time slices (Carvajal et al., 2019). DAM hydropower has the possibility of inter-seasonal energy storage through a flexible annual availability factor, while ROR hydropower's energy output is fixed through a seasonal availability factor. To assess the change of these availability factors across the modelling horizon (from 2015 to 2050), a hydrological simulation model soft-linked to a hydropower simulation model was used to simulate the operation of representative hydropower stations in each of the six river basins (Carvajal et al., 2017). Projections of hydrometeorological data that are inputted into the hydrological model correspond to the Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathway 4.5 (RCP4.5).[5] This analysis results in the annual average availability factor of hydropower in Ecuador increasing by 4% by 2050 compared to the historic trend. However, we consider also the possibility of a 25% reduction by 2050, using the standard deviation of a large ensemble of 40 Global Circulation Model projections to inform the minimum limits of runoff available for hydropower generation. To simulate the *lumpy* investment characteristics of hydropower,[6] the model can endogenously choose to invest in large and medium-sized hydropower capacity in discrete steps, while investments in small hydropower are treated in a linear fashion, according to the potential and the number of projects in each of the six river basins (Fig. 2,c).

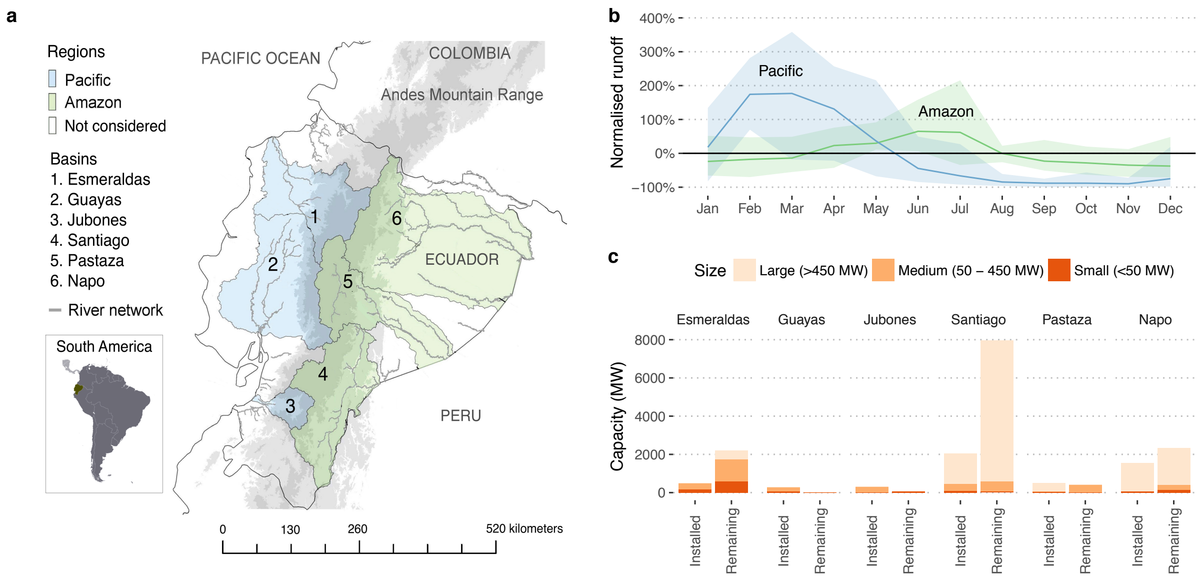

Figure 2. (a) Ecuador's main hydrographic regions and basins, (b) Average normalised runoff in the Amazon and Pacific regions (2006-2015). The shaded areas show the range of maximum and minimum runoff registered values. (c) Installed and remaining hydropower potential in Ecuador per basin.

2.2. Scenario design

This assessment distinguishes five different scenarios that capture a range of challenges to the future possible deployment of hydropower, summarised in Table. The NDC represents a continuation of Ecuador's current national hydropower-led energy policy as set out by Ecuador's Electricity Master Plan (MEER, 2017), which is aligned with the NDC recently presented under the Paris Agreement (UNFCCC, 2019). Therefore, the NDC scenario forces investment of 3.15 GW of new hydropower between year 2018 and 2025, simulating that the expected NDC-oriented expansion plan is accomplished. Beyond 2025, no hydropower or any other technology is forced into the system. The dry climate scenario (DRY) considers decreasing levels of runoff due to climate change. This is implemented in the model reducing by 25% the availability of hydropower by 2050, compared to historic availability levels (Carvajal et al., 2017). The no large hydro scenario (NLH) assumes the cancellation of planned large hydropower projects (>450MW) due to social and political opposition or the impossibility of securing investment in large infrastructure. This scenario reduces remaining hydropower potential in the model from 13 GW to only 3.2 GW and allows investment only in small and medium-sized hydropower projects. The cost and price overrun scenario (OVR) considers the uncertainty of overruns in the investment cost of electricity generation infrastructure, namely hydropower (ROR and DAM), thermoelectric (fossil fuel, biomass, biogas, geothermal and concentrated solar power), wind (onshore only) and solar facilities (distributed and utility scale). In addition, the uncertainty of fossil fuel prices (oil, oil products and gas) has been taken into consideration given that it also impacts the operation costs of thermal power plants and therefore the least-cost optimisation process of the model. The recurring uncertainty of construction cost overruns associated with electricity generation technologies and the volatility of fossil fuel prices has been integrated in TIMES-EC with a probabilistic approach that allows the model to minimise both cost and cost-risk simultaneously (Nijs & Poncelet, 2016). Finally, the diversified scenario (DIV) is used to explore how Ecuador might achieve the GHG reduction targets implied in the NDC scenario through a more diversified power matrix without the deployment of large hydropower infrastructure. This scenario is implemented by capping emissions at the expected level of the NDC scenarios and restricting large hydropower in a similar fashion to the NLH scenario. Further methodological and data details on these scenarios are found in the Supplemental Material.

To model demand evolution in Ecuador, a single scenario has been used that assumes annual growth rates of population (0.67%) and GDP (2.7%) according to national data from the Shared Socioeconomic Pathways 2 (SSP2) narrative developed by the International Institute for Applied System Analysis (IIASA) (Riahi et al., 2017). The SSP2 depicts a world that follows a path in which social, economic, and technological trends do not shift markedly from historical patterns (Dellink et al., 2015; Riahi et al., 2017), thus presenting a high GDP growth figure for Ecuador that could be difficult to maintain consistently over the modelling horizon. However, the SSP2 is the middle-of-the road case in the SSP ensemble and using these values allows for intercomparison with other climate policy assessments (Lucena et al., 2018). Please see Supplemental Material for further details.

Table 1. Overview of scenarios.

Scenario		Description
NDC	Nationally Determined Contribution	Deploy hydropower according to Government plans and conditional NDC until 2025 (forcing investment of 3.6 GW of hydropower between 2018 and 2025).
DRY	DRY climate	Occurrence of dry climate change scenario that progressively reduces available runoff (reduction of hydropower availability in 25% until 2050).
NLH	No Large Hydro	Restriction of new large hydropower, only medium and small hydropower (reduction of remaining potential from 13 GW to 3.2 GW).
OVR	Cost and price OVerRun	Consider cost overruns of electricity investment cost and fossil fuel prices with historic probability distributions integrated into the model.
DIV	DIVersified	Emission cap implied in the Government conditional NDC and no large hydropower allowed similar to the NLH scenario.

3. Results

3.1. Power generation and demand pathways for Ecuador

It is found that for Ecuador and the modelled scenarios, installed electricity generation capacity would reach between 16 – 17.6 GW, and electricity generation between by 66 – 72 TWh/y, by 2050, which is up to a three-fold increase compared to current levels (Table 2). All scenarios imply the deployment of large fractions of hydropower in the electricity mix and confirm that hydropower would remain an important least-cost source of electricity for Ecuador in the long-term (see Fig. 3,a,b). However, the share of total electricity supplied by hydropower varies significantly from a low of 53% in the NLH scenario to a maximum of 81% in the NDC scenario in 2050.

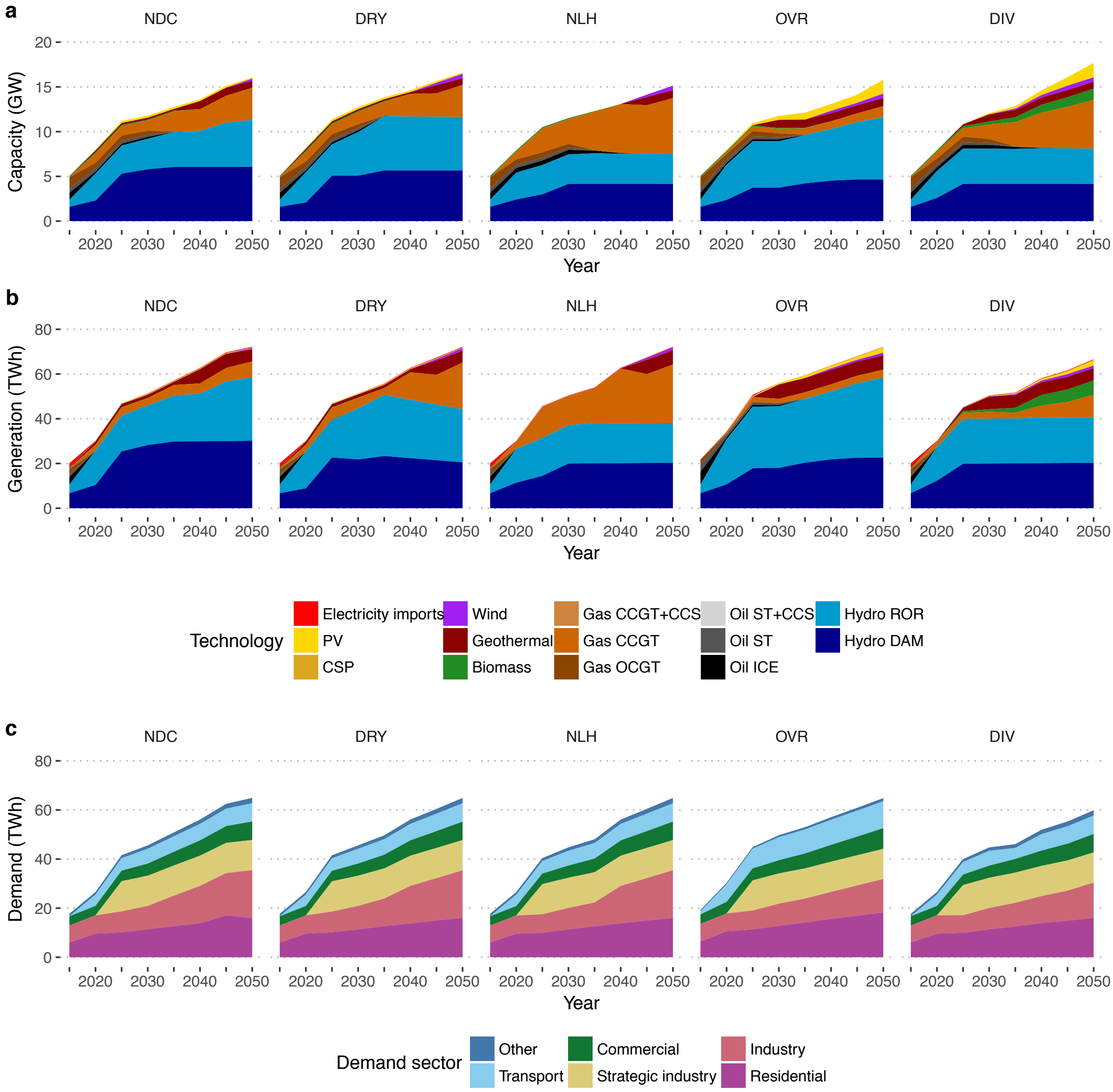

Figure 3. (a) Electricity installed capacity, (b) generation and (c) demand in Ecuador per scenarios for the period 2015-2050.

Note. PV: solar photovoltaic utility scale; wind: on-shore wind; biomass: bagasse-fired steam plants; OCGT: open cycle gas turbine; ST: steam turbine; ICE: internal combustion engine; CCS: carbon capture and storage; ROR: run-of-river hydropower; DAM: reservoir hydropower. Non-renewable fuels include: natural gas (Gas) and liquid fossil fuels (Oil) such as residual fuel oil, heavy fuel oil and diesel. Electricity demand considers strategic industries' power demand separately as planned by Ecuador's industrial policy plan (MCPEC, 2016).

Table 2. Main results for installed capacity and annual average generation in Ecuador per scenario by 2050.

	Technology	2017	Scenario in 2050				
			NDC	DRY	NLH	OVR	DIV
Capacity (GW)	**Total**	**7.3**	**16**	**16.6**	**15.1**	**15.8**	**17.6**
	Hydro	4.4	11.3	11.6	7.5	11.6	8.0
	Fossil	2.7	3.5	3.5	6.2	1.3	5.5
	Other renewables	0.2	1.2	1.5	1.4	2.9	4.1
Generation (TWh)	**Total**	**24.5**	**72.2**	**72.1**	**72.1**	**72.0**	**66.6**
	Hydro	20.4	58.6	44.2	38.0	58.4	40.6
	Fossil	3.6	7.0	20.9	26.2	3.6	10.1
	Other renewables	0.5	6.6	7.0	7.9	10.1	15.9
	Hydro share in generation	83%	81%	61%	53%	81%	61%

The NDC and DRY scenarios show a similar configuration with a system dominated by hydropower and gas-fired thermoelectric capacity. Notice that gas-fired capacity is the same in the NDC and DRY scenario in 2050 (3.5 GW), but from a generation perspective, these plants play different roles. Even though the NDC scenario strives for a matrix with large fractions of hydropower, still a significant amount of gas-fired capacity has to be installed to supply the system during hydropower shortages happening in the dry season (November to January). Gas-fired capacity would remain idle during the wet season and suggests that no matter the large amount of hydro installed capacity, thermal back-up is likely to be required for dry months of the year with or without the occurrence of a dry climate scenario. The NDC scenario also shows the highest proportion of reservoir hydropower (DAM) capacity (5 GW) compared to any other scenario. Once the DAM capacity intended by the Government is installed until 2025, further hydropower expansion only considers run-of-river hydropower (ROR) for the remainder of the time horizon. This potentially draws into question whether or not the Ecuadorian Government's focus on very large DAM projects is the best approach from a cost-optimal strategy.

In comparison, the DRY scenario shows gas-fired capacity playing a much larger and constant role throughout the year – it is found that a 25% reduction in hydropower availability due to climate change in 2050 would cause gas-fired thermal generation to be three times larger (20.9 TWh) than in the NDC scenario (7.0 TWh), which considers close to historic hydroclimatic conditions. Gas can offer a dispatchable electricity generation technology (through combined cycle gas turbines, CCGT) that is less sensitive to climatic variations, and appears to effectively fill in the gap created by the lack of large hydropower capacity in the DRY scenario. Thus, the modelled DRY scenario ironically suggests that carbon-emitting natural gas can be a least-cost adaptation measure, despite the fact that this would itself contribute again to GHG emissions. Notice also that hydropower generation declines towards 2050 in the DRY scenario and that extending the modelling horizon and the dry climate trend projection, for example up to 2100, would show stranded hydropower infrastructure contributing lower shares of energy to the power system.

The scenario with restricted investment in additional large hydropower projects (NLH) results in the lowest hydropower installed capacity among all scenarios (7.5 GW). However, despite the restrictions on large hydropower capacity, the results show that a significant fraction of small and medium sized hydropower may still be cost-optimal to deploy (3.1 GW). The restriction of large hydropower comes with a drawback — the NLH scenario involves the highest investment in gas-fired thermal plants amongst all of the scenarios (6.2 GW in 2050) and shows the potential for a lock-in to natural gas in the power sector. Ecuador has a relatively small level of proven domestic natural gas reserves (10.9 billion m^3) (OPEC, 2017), and therefore the country would likely need to build import and regasification infrastructure to obtain the required natural gas. This has clear implications for Ecuadorian energy sovereignty that run counter to domestic policy imperatives that are pushing for domestic hydropower generation (MICSE, 2016a). For example, energy security could be negatively impacted in the event that natural gas import contracts cannot be secured in a timely fashion or in the event that sufficient on-shore or even floating storage regasification units are not built in due time.

The NDC, DRY and NLH scenarios suggest that Ecuador could remain with its traditional hydrothermal[7] dominated power system with minimum shares of non-hydro renewables. In these three scenarios, geothermal energy is the only non-hydro renewable technology that has any relevance, supplying around 10% of electricity in 2050, suggesting that from a least-cost perspective all available geothermal potential should be exploited (0.9 GW) (ARCONEL, 2015). The uptake of other types of non-hydro renewable energy only becomes more pronounced in our model results when either the overruns of electricity generation technology costs and fossil fuel prices are considered in the optimisation process (OVR); or when a GHG emission cap is set in place combined with restrictions on large hydropower deployment (DIV).

Hydropower has uncertainties associated with investment cost overruns, while fossil fuel-based thermal plants have uncertainties associated with their operational costs (volatility of oil products and gas prices), both of which have been considered in the OVR scenario. Our modelling suggests that large shares of hydropower (11.6 GW) combined with PV (1.5 GW), geothermal (0.9 GW), wind (0.5 GW) and an almost complete phase-out of natural gas capacity is the preferred least-cost pathway to reduce cost-risk of the energy system by 2050. This result might seem counter intuitive from a sectoral power perspective, since it would appear that the optimum would be to lower the share of probably more expensive hydropower infrastructure. Nonetheless, from a whole energy system perspective, hydropower reduces the cost-risk of the overall energy system by reducing the demand of imported natural gas with uncertain volatile prices in the long-term. In other words, uncertain hydropower investment costs are preferred over uncertain operational costs for thermoelectric and other demand technologies consuming fossil fuels. The OVR scenario is the one that least relies on natural gas and has the earliest deployment dates for geothermal, wind and PV technologies. In addition it shows a significant preference for ROR over DAM type hydropower plants, the latter being much more expensive and with cost overruns that are considered not to be worthwhile to hedge against cost risk uncertainty.

The DIV scenario shows the largest total installed generation capacity out of all scenarios by 2050 (17.6 GW). Restrictions in large hydropower capacity and GHG-emitting thermoelectric generation is compensated by deploying larger capacities of solar PV (1.6 GW), biomass (1.2 GW), geothermal (0.9 GW) and wind (0.5 GW). Given the larger shares of intermittent generation capacity from intermittent renewables, the model also installs gas-fired generation capacity in a proportional fashion in order to provide back-up to the system (at similar levels to the NLH scenario). However, due to the emissions cap, biomass generation makes its appearance in this scenario as a flexible technology to buffer both seasonal variations of hydropower and the intermittency of PV and wind. In none of the scenarios does the model choose to deploy further oil generation capacity or any carbon capture and storage (CCS) technologies. The Ecuadorian NDC is currently focused on decarbonising the power sector through the deployment of large hydropower infrastructure. Considering a more ambitious goal for deep decarbonisation of the entire energy system would inevitably increase the pressure on hydropower and might show Ecuador's remaining potential as insufficient causing expensive technologies such as CCS, Direct Air Capture and concentrated solar power (CSP), among others, to emerge in the optimal solution.

One of the advantages of using an energy system optimisation model is that the interactions between supply and demand can be captured, the latter reacting to the expected energy prices from the supply side. Electricity demand across the different economic sectors is projected to increase between 60 – 65 TWh by 2050 as shown in Fig. 3,c. Electricity demand growth varies depending on socio-economic drivers and the electricity generation prices resulting from different scenarios (discussed further below). In general, the modelled projections see the residential and industrial sectors becoming the largest consumers of electricity by 2050. The NDC, DRY and NLH scenarios which maintain the hydrothermal dominated mix in the power sector do not show much variation in energy demand (65 TWh in 2050) or sectoral composition. The OVR scenario also shows a similar level of demand, but differs markedly in that it has a larger share of electricity destined to supply the transport sector. Given that the OVR scenario is one where the model considers the volatility of fossil fuel prices for the whole energy system, the uptake of electric vehicles can be thought of as a response for the whole energy system that hedges it against fossil fuel price risk. The DIV scenario shows the lowest level of electricity demand out of all scenarios (60 TWh in 2050), due to a more expensive power generation system. This increase in costs results in limited fuel switching, and households refrain from switching from LPG to electricity for cooking and domestic water heating. It must be noted that the differences registered in the power sector due to the different scenarios translate only to small variations in final energy demand, mainly because the electricity sector is projected to be only a small part of the energy system by 2050 and that the largest consumers, which are the industrial and transport sectors, are still mostly dependant on fossil fuels.

3.2. Power sector GHG emissions and costs

Regarding electricity related emissions, the study finds that the annual emission reductions achieved between 2015 and 2020 through hydropower development (Fig. 4,a) could be significantly overturned by a scenario that restricts large hydropower deployment (NLH) or the occurrence of a dry climate change scenario (DRY). Restricting the deployment of large hydropower, while not setting any cap for emission levels (NLH) could lead to a lock-in to gas-fired power generation and a steep increase in annual emissions (27 $MtCO_2e$) by 2050, compared to the implied annual level of the NDC scenario (7 $MtCO_2e$). Similarly, the low availability of runoff due to a dry climate change scenario (DRY) would reduce hydropower output and cause an increase in annual emission levels (22 $MtCO_2e$) by 2050. We find that restricting large hydropower can cause a fourfold increase in cumulative emissions (640 $MtCO_2e$) compared to NDC implied levels (176 $MtCO_2e$), while a 25% reduction of hydropower availability due to climate change would cause cumulative emissions to double (341 $MtCO_2e$) compared to NDC implied levels. Nonetheless, we find that Ecuador's NDC emission targets could still be achieved and maintained at lower levels by 2050 in two cases without large hydropower. The first of these cases compensates for the loss of large hydropower by deploying a diversified generation portfolio with more non-hydropower renewable energy (DIV), while the second features a hybrid geothermal-hydropower based power system that allows almost a total phase-out of fossil fuels in the matrix (OVR). Both of these cases result in consequences for system costs as explained below.

The variety of scenarios assessed with an energy system optimisation model has evidenced the interrelation between GHG emissions and system costs for the modelling period, which results in a trade-off driven by the share of hydropower in the power generation matrix. Fig. 4,b shows this trade-off and how average generation costs[8] seem to be highly sensitive and directly correlated to the share of hydropower generation in the power matrix, while cumulative emissions are inversely correlated. The OVR scenario presents the highest average generation cost (15 US¢/kWh) and lower-than-NDC emission levels (165 $MtCO_2e$) if policy makers adopt a risk averse attitude and factor in the uncertainty of costs and prices in their energy system optimization modelling assessments. The DIV scenario (181 $MtCO_2e$) would ensure compliance with Ecuador's international objectives under its NDC without large hydropower, but with the consequences of a power system with an average generation cost (12 US¢/kWh) that is around 54% higher than the scenario that does allow for large hydropower deployment (8 US US¢/kWh). The NLH and DRY scenarios have generation matrixes with larger shares of natural gas and consequentially much greater cumulative emissions by 2050, though their average generation cost is not much lower than the NDC scenario. Thus in terms of cost, it does seem sensible to pursue the hydropower-based scenario, but only if future projections of climate change favour increased precipitation, hydropower project budgets are kept in check and damages to social and environmental surroundings are kept to a minimum (i.e. with ROR instead of DAM type).

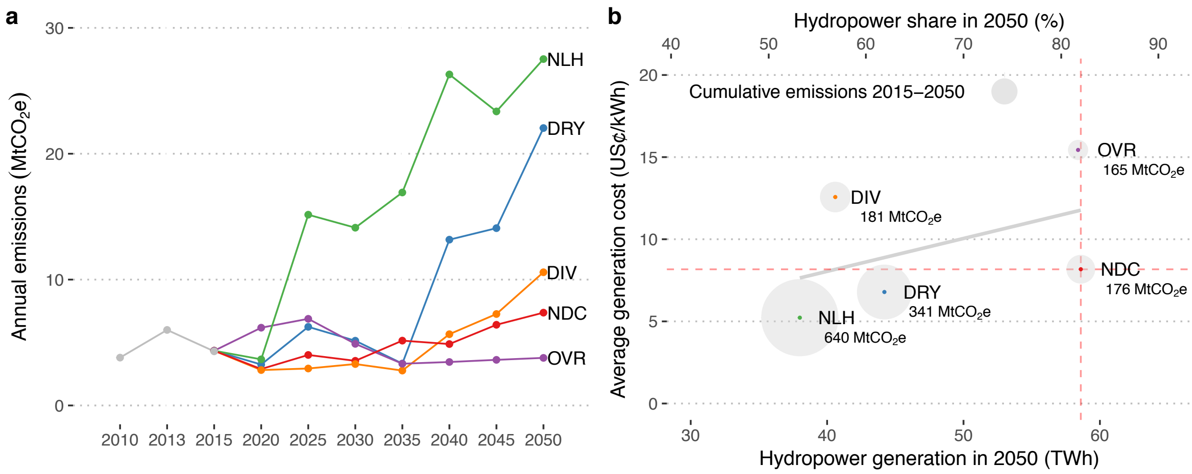

Figure 4. (a) Evolution of annual electricity-related GHG emissions. (b) Trade-off among hydropower generation, average generation cost and total cumulative GHG emissions for the 2017-2050 period.

4. Conclusions

This study has demonstrated that hydropower will keep on playing an important role in Ecuador's power sector. At the same time it has given important insights on how the particular challenges for hydropower deployment can impact the technological configuration, costs and emissions of the power system. Rather than providing an analysis at the plant level or assessing challenges separately, a key strength of the used whole energy system modelling approach is that it captured trade-offs between actions for a broad range of scenarios, and allowed for full emissions accounting. The analysis shows that whereas the current electricity generation portfolio of Ecuador is a hydrothermal one dominated by large scale hydropower, the future could hold a number of different configurations. Which of these eventually might transpire will have implications for system costs and Ecuador's ability to meet its NDC targets. Table 3 summarises these trade-offs together with the greatest challenges for the energy sector in each of the scenarios assessed in this paper.

Table 3. Scenario trade-off analysis relative to the NDC scenario.

	Scenario				
	NDC	DRY	NLH	OVR	DIV
Hydropower generation in 2050	58.6 TWh	-25% ↓	-35% ↓	-1% ↓	-31% ↓
Cumulative emissions 2017-2050	176 $MtCO_2e$	100% ↑	282% ↑	-11% ↓	0% –
Average generation cost 2017-2050	8.1 US¢/kWh	-17% ↓	-36% ↓	89% ↑	54% ↑
Challenge for the energy sector	Need for thermal for backup despite large hydropower capacity	Dependency on imported gas, stranded hydropower infrastructure, high emissions	Dependency on imported gas, high emissions, high emissions	Early deployment of geothermal energy, expensive system	Need for gas-fired thermal back-up for intermittent renewables, expensive system

No single scenario is able to simultaneously achieve low emissions, low costs and offer resilience against the risks of future hydropower deployment. It is shown that Government plans to promote large hydropower up to 2025 have the potential to deliver a power system with low GHG emissions. However, there is still likely to be a need for thermal generation to provide back-up during the dry seasons of the year. This existing strategy of large hydropower deployment is also vulnerable to the occurrence of a dry climate scenario as well as the possibility that societal resistance could limit plans for large-scale hydropower deployment. A dry climate scenario could result in stranded hydropower assets in the long-term and in greater use of gas-fired generation and consequential increases in emission levels, making GHG emissions reductions that are comparable to the NDC impossible to achieve. Similarly, restricting the deployment of large hydropower can also lead to a gas-dominated power system which has lower system costs but high GHG emission levels, which are likely to be problematic when more stringent emission reduction efforts (due to international commitments and the Paris Agreement ratcheting mechanism) are set in place, and could create stranded assets out of proposed new thermoelectric infrastructure (Pfeiffer et al., 2018). Natural gas appears to be the *de facto* least-cost alternative to reduced hydropower expansion and generation, hence revealing the need for even greater reductions in capital costs of non-hydro renewable technologies and lower-cost utility scale electricity storage. The introduction of a social price of carbon (tax) could also cause the model to yield different results in terms of the uptake of non-hydro renewable energy, fuel switching and energy efficiency measures in the overall energy system. At the moment there is no discussion or policy suggestions in Ecuador that would lead the country towards a price for carbon (although in the future this could be set at the international level). This could be an area for future research.

In this study, the diversification of the power system with a greater uptake of non-hydro renewables has only been achieved if fossil fuel price volatility and electricity infrastructure cost-overruns are factored-in to the decision-making logic of the energy model, or if GHG emissions are capped to match the levels of the NDC while simultaneously limiting large hydropower deployment. In either of these cases, geothermal and biomass energy would need to replace natural gas in covering peak-load and back-up for intermittent PV and wind. In both cases, the costs of the electricity system are higher than the traditional hydrothermal system equivalents. We should also highlight that those scenarios employing Ecuador's biomass resources could also be exposed to climate vulnerabilities due to the effects of higher temperatures and extreme hydrological conditions (Cronin et al., 2018). The use of biomass for energy generation also brings with it a broader set of social and environmental concerns (land use competition with food crops, for example), that should be factored into future research efforts. This could be done, for example, by including a land use, land use change and forestry (LULUCF) module into the energy system analysis to assess biomass availability and carbon sinks (Rochedo et al., 2018). However, considering that the use of biomass for power generation is still incipient in Ecuador and that the country's agricultural based-economy allows for a large supply of biomass waste, the use of biomass can well be considered a viable option.

The IPCC Special Report on Global Warming of 1.5°C has shown that existing NDC commitments are insufficient and that countries need to quickly implement pathways to deep decarbonisation by mid-century in order to have a chance of limiting global warming to 1.5°C (IPCC, 2018). Ecuador's NDC for the energy sector only considers emission reductions achieved by hydropower projects that have already been commissioned and future projects according to the country's electricity expansion plan. We find that this plan has its advantages in terms of power system costs and emissions, but it certainly would not be enough to set the country on a path of a low carbon energy system – electricity accounts only for 13% of total final energy demand (MICSE, 2016b). Although TIMES-EC represents the whole energy system of Ecuador, in which both supply and demand have been modelled endogenously, the focus of this study has been on the role of hydropower and its representation in a long-term energy system model. In the context of long-term capacity expansion planning of the power system, in which the objective is to understand required investments and the interaction of the whole energy system, the representation of hydropower operation at the seasonal and annual level as done in this paper is sufficient. However, the time-scale resolution of the model does not allow for the full value of hydropower to be captured (a typical limitation of long-term energy system optimisation models). While this is unlikely to significantly change the core insights presented in this paper, in which hydropower would still have a leading role in the future of Ecuador, a finer time-scale resolution at the hourly level might better allow to explore in detail hydropower's role to complement intermittent renewable energy and further reduction potential of energy-related emissions through improved efficiency and sector coupling in the end-use demand sectors, particularly with electric vehicles in the transport sector – the country's largest fossil-fuel energy consumer, with 48% of final energy demand (MICSE, 2016b). This offers an opportunity for further research by soft-linking TIMES-EC to a power dispatch model with higher time and spatial resolution (Deane et al., 2012; IRENA, 2018).

Beyond the Ecuadorian context, the results of this exercise can serve as an important reference for other developing countries and regions where there is still large untapped hydropower potential (i.e. in Southeast Asia and Africa). It is suggested that model-based long-term energy scenarios that consider expanding large shares of hydropower take into consideration the following good practices to enhance their validity and utility. The first of these is to perform an *ex-post* analysis of local and regional hydropower project cost and schedule overruns rather than using international references, as well as an analysis of resource potential restrictions due to socio-environmental opposition, which can greatly influence the least-cost solution of the optimisation model. The second, is to consider a broad uncertainty range of hydroclimatic projections, which could significantly differ from the historic trends and the ensemble average of climate projections. Producing scenarios with low flows reveals the alternative generation technologies that could surge to compensate the lack of hydropower or the need to import electricity from neighbouring nations. Finally, it is important to benchmark the main challenges that threaten hydropower development in the long-term, with use of whole energy system models as was presented in the methodology of this study. Exploring the broader energy system allows to systematically assess the trade-offs between global emission targets (NDCs or net-zero emissions scenarios), power system configuration and cost, which ultimately is a practical tool for debate in the energy and climate policy making arena.

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[1] Recurring uncertainty is characterised by conditions that are periodically recurring and in which knowing the past or current value of the parameter does not resolve the uncertainty for the future.

[2] Total hydropower potential is 22.1 GW, of which 5.1 GW have already been installed (of which 0.7 GW is under construction); 13 GW is considered as the effective remaining potential that can be tapped at reasonable costs; and 4 GW have been determined as unfeasible due to environmental restrictions (within natural parks or high biodiversity areas).

[3] Techno-economically feasible hydropower potential, in the Ecuadorian context, refers to the total capacity of hydropower projects with technologically feasible construction complexity at reasonable or industry-standard investment costs.

[4] Availability factor, a ratio of hydropower production over the maximum theoretical production, subject to a defined time period.

[5] A Representative Concentration Pathway (RCP) is a greenhouse gas (GHG) concentration trajectory adopted by the IPCC (RCPs: RCP2.6, RCP4.5, RCP6, and RCP8.5). The number refers to the radiative forcing (in W/m^2) relative to pre-industrial levels expected by the end of the 21st century. The RCP4.5, is considered as a middle-of-the-road pathway that is consistent with radiative forcing of +4.5 W/m2 by 2100 (Moss et al., 2010).

[6] Constraining the model to use discrete sizes instead of a linear continuous expansion path, a method known colloquially as "lumpy investment", allows to capture the granularity of investments of large infrastructure.

[7] Hydrothermal system refers to thermoelectric power plants that operate synchronously with hydroelectric plants in order to increase the amount of energy that the system can guarantee by reducing deficits in dry seasons and avoiding spillage in wet seasons.

[8] Average generation cost is understood is the net present value of the unit-cost of electricity over the lifetime of a generating asset.

References

Anderson, E. P., Jenkins, C. N., Heilpern, S., Maldonado-ocampo, J. A., Carvajal-vallejos, F. M., Encalada, A. C., & Rivadeneira, J. F. (2018). Fragmentation of Andes-to-Amazon connectivity by hydropower dams. *Applied Ecology*, (January). https://doi.org/10.1126/sciadv.aao1642

Ansar, A., Flyvbjerg, B., Budzier, A., & Lunn, D. (2014). Should we build more large dams? The actual costs of hydropower megaproject development. *Energy Policy*, *69*, 43–56. https://doi.org/10.1016/j.enpol.2013.10.069

ARCONEL. (2015). *Inventario de recursos energeticos del Ecuador con fines de produccion electrica - 2015*. Retrieved from http://www.regulacionelectrica.gob.ec/wp-content/uploads/downloads/2015/11/Presentación-y-contenido-Inventario-Recursos-Energéticos-2015.pdf

ARCONEL. (2018). *Balance Nacional Electrico Enero 2018*. Retrieved from http://www.regulacionelectrica.gob.ec/estadistica-del-sector-electrico/

Bacon, R. W., & Besant-Jones, J. E. (1998). Estimating construction costs and schedules. *Energy Policy*, *26*(4), 317–333. https://doi.org/10.1016/S0301-4215(97)00164-X

Callegari, C., Szklo, A., & Schaeffer, R. (2018). Cost overruns and delays in energy megaprojects : How big is big enough ? *Energy Policy*, *114*(July 2017), 211–220. https://doi.org/10.1016/j.enpol.2017.11.059

Carvajal, P. E., Anandarajah, G., Mulugetta, Y., & Dessens, O. (2017). Assessing uncertainty of climate change impacts on long-term hydropower generation using the CMIP5 ensemble — the case of Ecuador. *Climatic Change*, *144*(4), 36–37. https://doi.org/10.1007/s10584-017-2055-4

Carvajal, P. E., Li, F. G. N., Soria, R., Cronin, J., Anandarajah, G., & Mulugetta, Y. (2019). Large Hydropower, Decarbonisation and Climate Change Uncertainty: Modelling Power Sector Pathways for Ecuador. *Energy Stategy Reviews*, *23*, 86–99. Retrieved from https://www.sciencedirect.com/science/article/pii/S2211467X18301202

CELEC. (2017). Estudios Proyecto Zamora-Santiago. Retrieved August 23, 2017, from https://www.celec.gob.ec/hidropaute/proyectos/31-espanol/proyectos/index.php

Cisneros, J., B.E., T. O., Arnell, N. W., Benito, G., Cogley, J. G., Döll, P., … Mwakalila, S. S. (2014). *Freshwater resources. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Vol. 1). Retrieved from http://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-Chap3_FINAL.pdf

Cronin, J., Anandarajah, G., & Dessens, O. (2018). Climate change impacts on the energy system: A review of trends and gaps. *Climatic Change*. https://doi.org/https://doi.org/10.1007/s10584-018-2265-4

Deane, J. P., Chiodi, A., Gargiulo, M., & Ó Gallachóir, B. P. (2012). Soft-linking of a power systems model to an energy systems model. *Energy*, *42*(1), 303–312. https://doi.org/10.1016/j.energy.2012.03.052

Dellink, R., Chateau, J., Lanzi, E., & Magne, B. (2015). Long-term economic growth projections in the Shared Socioeconomic Pathways §. *Global Environmental Change*, *42*, 200–214. https://doi.org/10.1016/j.gloenvcha.2015.06.004

Escribano, G. (2013). Ecuador's energy policy mix: Development versus conservation and nationalism with Chinese loans. *Energy Policy*, *57*, 152–159. https://doi.org/10.1016/j.enpol.2013.01.022

Gallagher, K. P., & Myers, M. (2015). China-Latin America Finance Database. Retrieved July 10, 2015, from http://www.thedialogue.org/mapList2/index.html#.VZ_fbefviag

Gernaat, D. E. H. J., Bogaart, P. W., Vuuren, D. P. Van, Biemans, H., & Niessink, R. (2017). High-resolution assessment of global technical and economic hydropower potential. *Nature Energy*, *2*(October). https://doi.org/10.1038/s41560-017-0006-y

IEA. (2018). *Key world energy statistics 2018*. Retrieved from https://webstore.iea.org/key-world-energy-statistics-2018

IHA. (2017). *Hydropower Status Report 2017*. Retrieved from https://www.hydropower.org/2017-hydropower-status-report

IHA. (2018). *Hydropower status report 2018*. Retrieved from https://www.hydropower.org/sites/default/files/publications-docs/iha_2018_hydropower_status_report_digital_copy.pdf

IPCC. (2018). *Global warming of 1.5 °C - Summary for Policymakers*. Retrieved from http://report.ipcc.ch/sr15/pdf/sr15_spm_final.pdf

IRENA. (2018). *POWER SYSTEM FLEXIBILITY FOR THE ENERGY TRANSITION PART II : IRENA FLEXTOOL METHODOLOGY*. Bonn, Germany. Retrieved from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Nov/IRENA_Power_system_flexibility_2_2018.pdf?la=en&hash=B7028E2E169CF239269EC9695D53276E084A29AE

Loulou, R., & Labriet, M. (2008). ETSAP-TIAM: The TIMES integrated assessment model Part I: Model structure. *Computational Management Science*, *5*(1–2), 7–40. https://doi.org/10.1007/s10287-007-0046-z

Lucena, F. P., Hejazi, M., Vasquez-arroyo, E., Turner, S., Daenzer, K., Rochedo, P. R. R., … Zwaan, B. Van Der. (2018). Interactions between climate change mitigation and adaptation : The case of hydropower in Brazil. *Energy*, *164*. https://doi.org/10.1016/j.energy.2018.09.005

MAE. (2012a). *Estrategia Nacional de Cambio Climatico del Ecuador*. Retrieved from http://extwprlegs1.fao.org/docs/pdf/ecu140074.pdf

MAE. (2012b). *Inventario Nacional de Gases de Efecto Invernadero del Ecuador*. Retrieved from https://info.undp.org/docs/pdc/Documents/ECU/06 Resumen Ejecutivo INGEI de Ecuador. Serie Temporal 1994-2012.pdf

MAE. (2017). *Tercera Comunicación Nacional del Ecuador*. Retrieved from http://www.ambiente.gob.ec/wp-content/uploads/downloads/2017/10/TERCERA-COMUNICACION-BAJA-septiembre-20171-ilovepdf-compressed1.pdf

MAE, FOCAM, & UNDP. (2015). *NAMA - Desarrollo de Centrales Hidroelectricas en el Ecuador*. Retrieved from https://info.undp.org/docs/pdc/Documents/ECU/NAMA DCH .pdf

MCPEC. (2016). *Politica Industrial del Ecuador 2016-2025*. Ecuador. Retrieved from http://www.industrias.gob.ec/wp-content/uploads/2017/01/politicaIndustrialweb-16-dic-16-baja.pdf

MEER. (2017). *Plan Maestro de Electricidad 2016-2025*. Ecuador. Retrieved from https://www.celec.gob.ec/hidroagoyan/index.php/plan-maestro-de-electricidad-2016-2025

MICSE. (2016a). *Agenda Nacional de Energia*. Retrieved from http://www.sectoresestrategicos.gob.ec/biblioteca/

MICSE. (2016b). *Balance Energetico Nacional*. Retrieved from https://issuu.com/sectoresestrategicos/docs/balance_energe__tico_2016

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., Van Vuuren, D. P., … Wilbanks, T. J. (2010). The next generation of scenarios for climate change research and assessment. *Nature*, *463*(7282), 747–756. https://doi.org/10.1038/nature08823

Nijs, W., & Poncelet, K. (2016). *Integrating recurring uncertainties in ETSAP energy system models*.

OPEC. (2017). *Annual Statistical Bulletin*. Vienna. Retrieved from http://www.opec.org/opec_web/static_files_project/media/downloads/publications/ASB2017_13062017.pdf

Parkinson, S. C., Johnson, N., Rao, N. D., Jones, B., Vliet, M. T. H. Van, Fricko, O., … Fl, M. (2016). Climate and human development impacts on municipal water demand : A spatially-explicit global modeling framework. *Environmental Modelling & Software*, *85*, 266–278. https://doi.org/10.1016/j.envsoft.2016.08.002

Pfeiffer, A., Hepburn, C., Vogt-schilb, A., & Caldecott, B. (2018). Committed emissions from existing and planned power plants and asset stranding required to meet the Paris Agreement. *Environmental Research Letters*. Retrieved from http://iopscience.iop.org/article/10.1088/1748-9326/aabc5f/pdf

Riahi, K., Vuuren, D. P. Van, Kriegler, E., Edmonds, J., Neill, B. C. O., Fujimori, S., … Tavoni, M. (2017). *The Shared Socioeconomic Pathways and their energy , land use , and greenhouse gas emissions implications : An overview*. *Global Environmental Change* (Vol. 42). https://doi.org/10.1016/j.gloenvcha.2016.05.009

Rochedo, P. R. R., Soares-Filho, B., Schaeffer, R., Viola, E., Szklo, A., Lucena, A. F. P., … Rathmann, R. (2018). The threat of political bargaining to climate mitigation in Brazil. *Nature Climate Change*, *8*(8), 695–698. https://doi.org/10.1038/s41558-018-0213-y

Schaeffer, R., Szklo, A., De Lucena, A., Soria, R., & Chavez-Rodriguez, M. (2013). The Vulnerable Amazon: The Impact of Climate Change on the Untapped Potential of Hydropower Systems. *IEEE Power and Energy Magazine*, *11*(3), 22–31. https://doi.org/10.1109/MPE.2013.2245584

Sovacool, B. K., Nugent, D., & Gilbert, A. (2014). Construction Cost Overruns and Electricity Infrastructure: An Unavoidable Risk? *The Electricity Journal*, *27*(4), 112–120. https://doi.org/10.1016/j.tej.2014.03.015

Spalding-Fecher, R., Joyce, B., & Winkler, H. (2017). Climate change and hydropower in the Southern African Power Pool and Zambezi River Basin : System-wide impacts and policy implications. *Energy Policy*, *103*(June 2016), 84–97. https://doi.org/10.1016/j.enpol.2016.12.009

UNFCCC. (2015). *Adoption of the Paris Agreement Proposal by the President*. Paris. Retrieved from http://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf

UNFCCC. (2019). *Ecuador's First Nationallay Determined Contribution*. Retrieved from https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Ecuador First/Primera NDC Ecuador.pdf

van der Zwaan, B., Boccalon, A., & Dalla, F. (2018). Prospects for hydropower in Ethiopia : An energy-water nexus analysis. *Energy Strategy Reviews*, *19*, 19–30. https://doi.org/10.1016/j.esr.2017.11.001

van Vliet, M. T. H., Wiberg, D., Leduc, S., & Riahi, K. (2016). Power-generation system vulnerability and adaptation to changes in climate and water resources. *Nature Climate Change*, (January). https://doi.org/10.1038/nclimate2903

Villavicencio, A. (2015). Un cambio de matriz energética bajo toda sospecha. Retrieved from https://lalineadefuego.info/2015/06/02/un-cambio-de-matriz-energetica-bajo-toda-sospecha-por-arturo-villavicencio/

WEC. (2015). *Charting the Upsurge in Hydropower Development*. Retrieved from https://www.worldenergy.org/publications/2015/2015-hydropower-status/

Winemiller, K. O., McIntyre, P. B., Castello, L., Fluet-Chouinard, E., Giarrizzo, T., Nam, S., … Saenz, L. (2016). Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. *Science*, *351*(6269), 128–129. https://doi.org/10.1126/science.aac7082