Energy Strategy Reviews 35 (2021) 100637

Contents lists available at ScienceDirect

Energy Strategy Reviews

journal homepage: http://www.elsevier.com/locate/esr

Long-term deep decarbonisation pathways for Ecuador: Insights from an integrated assessment model

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A R T I C L E I N F O

Keywords:
Integrated assessment model (IAM)
Deep decarbonisation
Net-zero emissions
Energy planning
Ecuador

A B S T R A C T

This work presents an Integrated Assessment Model (IAM) developed for Ecuador, the so-called Ecuador Land Use and Energy Network Analysis model (ELENA). This model includes six distinctive sectors of the economy and displays the four geographic regions composing the country. The model enables to capture sectorial interactions, under a set of scenarios designed to evaluate the energy and land perspectives until 2050. The model is a crucial planning instrument to evaluate public policies, such as National Determined Contributions (NDC) and even more ambitious decarbonisation scenarios. Findings show that Ecuador's NDC are not aligned with the "well below" 2 °C target, committed in the Paris Agreement. Moreover, to achieve deep decarbonisation it is necessary to endorse disruptive strategies in which bioenergy and reforestation play a main role. To keep under the 1.5 °C temperature threshold above pre-industrial levels, Ecuador's energy matrix must be diversified with higher shares of low carbon technologies and electrification of energy end use in the transport, buildings and industry sectors. Biomass with carbon capture and storage (BECCS) and biofuels could transform the energy sector in a CO_2 sink.

1. Introduction

Global climate change (CC) requires structured, decarbonisation action plans from every country. By the end of the century, temperature increase must reach a threshold value of 1.5 °C above preindustrial levels to avoid major ecosystem alterations [1]. Aligned with this goal, Paris agreement signatory countries, including Ecuador, have pledged their National Determined Contributions (NDCs) [2]. The agreement encourages the parties to develop and follow long-term development strategies toward limiting temperature increase to a "well below" 2 °C target, and pursue efforts to attain the 1.5 °C limit [3]. It also stipulates that greenhouse-gas (GHG) emissions peak must be reached as soon as possible and points out the difficulties that this could generate for developing countries [3]. However, concerns were raised about the convergence of NDC strategies with the GHG emissions level required to achieve the Paris Agreement global temperature targets [4]. Moreover, reaching a long term goal with short-term actions is not guaranteed [4–6]. In this context, building local modelling capacities is key to state national long-term decarbonisation strategies complying with the Paris agreement while consistently dealing with energy and Agriculture, Forestry and Other Land Use (AFOLU) GHG emissions.

The analysis of decarbonisation pathways requires a framework that captures the relations and trade-offs between the different sectors and strategies. Long-term integrated assessment models (IAMs) are established tools to study interlinkages between the human and the natural system at national and global scales [7–10]. Insights from these complex models are widely used to advise policymakers and to inform the general public [11]. Besides, the interaction between reforestation, deforestation, agricultural practices and the energy sector are well captured only by few IAMs [12]. This gap is a constant in low-developing economies of the Global South. Particularly in Latin America countries, where, to our knowledge, only Brazilian experts have developed a tool which is based on hard-link modelling between energy and land systems [13]. Understanding this sort of interaction is emblematic for Ecuador's case, where

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https://doi.org/10.1016/j.esr.2021.100637
Received 1 April 2020; Received in revised form 6 September 2020; Accepted 23 February 2021
Available online 23 March 2021

trade-offs between protecting its massive biodiversity [14] and the increased risk of land-use changes for agriculture and energy activities must be appropriately understood to create suitable and structured policies.

Moreover, Ecuador must prepare its energy sector to a substantial oil production reduction due to the resource exhaustion expected for the next decades [15]. In order to partially replace oil energy supply, bioenergy can be used, creating an additional land dispute controversy. In this context to assess sustainable transition pathways, Ecuador requires a model that assesses the long-term interaction between energy and land-use sectors. This work contributes to filling this gap.

The objective of this paper is to present an IAM developed for Ecuador, the so-called Ecuador Land Use and Energy Network Analysis model (ELENA). ELENA is used to test whether the current policies and proposed NDC would allow Ecuador to be aligned with the 1.5 °C target. In addition, this study applies a nested optimization of ELENA with a global IAM, the COFFEE[1] model [17], which provides national carbon budgets to regional and national IAMs [18]. By doing this, the ELENA model tackles decarbonisation strategies coherent with a global trajectory to limit GHG emissions. Thus, this study also assesses Long-term strategies (LTSs) to reduce GHG emissions in Ecuador to a global 1.5°C-compatible level by 2050. ELENA is the first Ecuadorian IAM able to model energy and AFOLU sectors in a detailed manner and in a single modelling framework, by hard linking both sectors. The tool has the potential to evaluate different policies and LTSs to better inform Ecuadorian and international stakeholders in the ongoing global climate change negotiations. The model was nationally developed under the aegis of the "Deep Decarbonisation Pathways Project for Latin America and the Caribbean (DDP-LAC[2])". It is based on the methods and framework of the Brazil Land Use and Energy System (BLUES) model [13], which modelling procedure could well be replicated, with adjustments, in other Latin American countries.

2. Literature review

The DDP-LAC project included other five countries in the region, namely Argentina, Colombia, Costa Rica, Mexico and Peru, which developed long-term decarbonisation pathways scenarios. All participating countries had the same objective; however, they applied different modelling tools and methodologies [87].

To our knowledge, at the time of writing, there is no literature that evidence using an IAM to assess Ecuador's energy and land use sectors in the context of decarbonisation, or in any other context for that matter. Several studies explore long-term energy system pathways for Ecuador for the transport sector [19,20], the impacts of energy efficiency [21,22], renewable energy for power generation [23] and NDC scenarios [24]. Nevertheless, none of these studies explore Paris Agreement-compliant scenarios for deep decarbonisation by mid-century, nor take an integrated methodological approach. Ecuador's NDC itself was indeed informed with long-term scenarios modelled with the LEAP platform [25]. However, only the energy sector was modelled without considering interlinkages with the AFOLU sector.

The current expansion and operation planning of the Ecuadorian electric power system [26], carried out by the Ministry of Energy is based on two computational tools: OPTGEN (model for generation expansion planning and regional interconnections), and SDDP (stochastic hydrothermal dispatch with network restrictions), both commercial software provided by PSR [27]. The OPTGEN model starts with an exogenous demand forecast and project inventory and determines the least-cost expansion plan (investment, operation and maintenance). These results are subsequently integrated into the SDDP model, which considers the uncertainty of runoff and the operational restrictions of generation plants. However, a significant drawback of this planning process is its time horizon (10 years), limited by the number of years that can be assessed at the hourly level with the mentioned models. Considering that GHG emissions are notably a long-term issue, with horizons from mid-century onwards, it is myopic to base long-term planning only with a 10-year horizon. Moreover, these tools only refer to the electric power system, not including an overall assessment of other energy-related facilities, such as oil production and refining and detailed analysis of end uses. Finally, the mentioned models were not developed to deal with GHG emissions, mitigation options and climate policy.

Following this introductory section, section two gives an overview of Ecuador's energy and AFOLU sectors; section three showcases the methodology used for this study; section 4 presents results and section 5 discusses them. Section 6 gives the overall conclusions and areas for further work.

3. Ecuador's energy and land use overview

The country's largest share of GHG emissions derives from fossil fuel combustion and land-use change (see Fig. 1). Emissions in the latter sector are mainly related to the expansion of the agricultural frontier and illegal deforestation [28]. The energy industry sector ranks only fourth given that generation heavily relies on hydropower, mostly on large scale plants built during the last decade [29].

Hydropower accounted for 84% of total electricity generation share in 2018 [30]. Most of the remaining Ecuadorian hydroelectric potential lay in the Amazon region [31], with some 13 GW of techno-economic and environmental potential [32]. Nevertheless, using this potential with large hydropower plants would cause substantial local environmental and social impacts [33,34]. Moreover, including more hydropower plants in the Amazon watershed would not solve the production reduction due to the drought season (October to December) [35]. This situation will likely worsen because of the effects of climate change on the rain pattern in the region [36,37].

Electricity access is relatively high (97.3%) [38,39], but electricity represents less than 16% of the total final energy consumption (see Fig. 2). The commercial sector has the highest electrification share with almost 60%, while electricity in the transport sector only represents 0.01% of the total energy consumed in this sector [39]. Meanwhile,

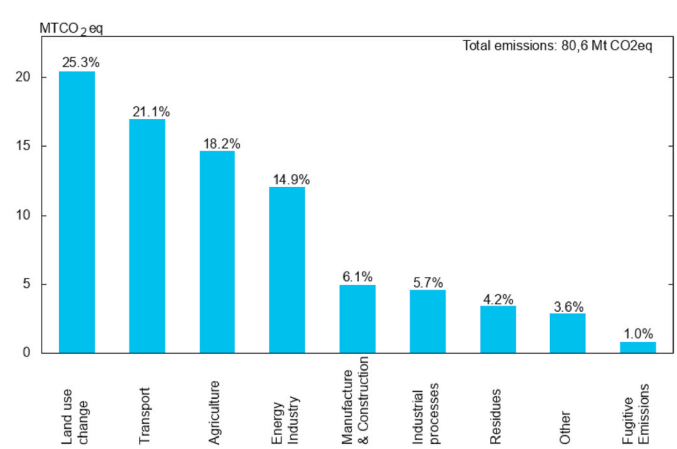

Fig. 1. GHG emissions Ecuador by sector in 2012 [28].

[1] The COmputable Framework For Energy and the Environment (COFFEE) model is a global integrated model created in the Center for Energy and Environmental Economics (Cenergia Lab), an integrated research laboratory of the Energy Planning Program, Graduate School of Engineering, Universidade Federal do Rio de Janeiro (PPE/COPPE/UFRJ), in Brazil. For more details, see Ref. [16].

[2] This project was financed by the Inter-American Development Bank (IADB) and technically managed by the Institute for Sustainable Development and International Relations (IDDRI).

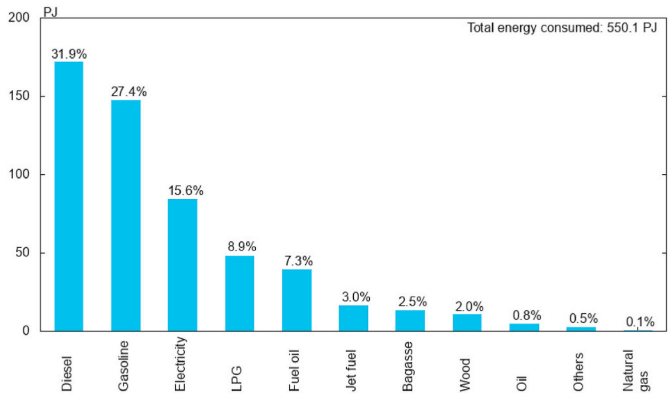

Fig. 2. Final energy consumption in 2016, share by source [40].

households and industrial electricity consumption account for, respectively, 37% and 46% of the total energy consumed by each sector [39]. Thus, there is a significant margin to increase electrification in most of the sectors, especially transportation.

The transport sector accounts for almost a fifth of the country's GHG emissions and almost half of the total final energy consumption. Road transport dominates in Ecuador, and 63% of energy is consumed by heavy, medium and light freight transport (see Fig. 3). Consequently, the main fuels used are diesel and gasoline, representing 52.7% and 45.6% of the final energy consumed in the transport sector, respectively [39]. It should be pointed out that 60% of these oil products are currently imported [29]. Furthermore, fuels in Ecuador are highly subsidised [41], leading to inefficiency in consumption and accelerated growth of private vehicles fleet for individual use, generating mobility issues in the main cities. The two largest cities in Ecuador, Quito and Guayaquil, are among the 30 most congested cities in the world, being respectively at place 20th and 23rd in the "Time Lost in Congestion" ranking [42]. There are significant challenges to making structural changes to the current state of transportation in Ecuador. For instance, current efforts in 2019 to deal with fuel subsidies led to major turmoil in the country [41]. Despite the difficulties, local governments in the main cities make efforts to develop massive public electric transport systems, such as the Quito metro, the Cuenca tram and the Guayaquil airway. Finally, an eventual shift toward electrification in passenger transportation still presents significant challenges such as infrastructure, high cost of battery electric vehicle (BEV) and effects on the power sector. Despite that, the government has claimed an ambitious plan to electrify urban busses [43].

Ecuador faces economic and energy security risks associated with its significant dependency on oil production. In 2015, crude oil represented more than one-third of the export revenues [29,44]. Besides, under current production rates Ecuador could reach its crude oil production peak between 2024 and 2027 [15,45]. This would be a turning point for the country's energy and economic policies, bringing challenges not only for the energy sector but also consequences in terms of trade deficits. This situation will be exacerbated if the current level of energy subsidies is maintained. Besides its macro-economic importance, crude oil and oil products represent 80% of the Ecuadorian final energy consumption – see Fig. 2. Although Ecuador is a net oil exporter with an average daily production of 518 thousand barrels per day [39], 70% is exported and domestic refineries process the remainder. Local refining supplies less than 50% of oil product demand, whilst the rest is imported [39].

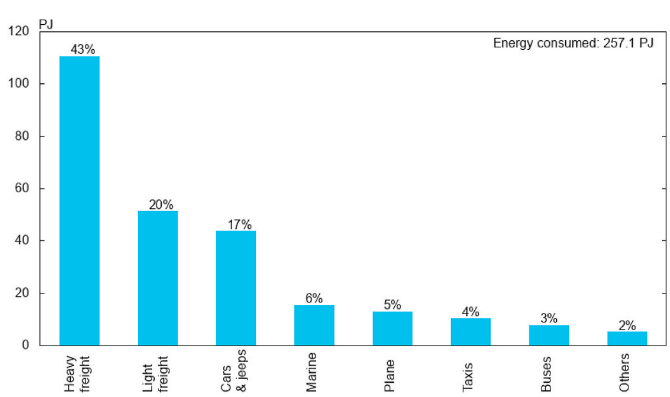

Fig. 3. Energy consumed in the transport sector in 2016 [40].

In this context, Ecuador faces a challenging combination of problems in the energy sector that can have a repercussion in the land sector. As the remaining petroleum resources are available mainly in the Amazon region, its extraction implies a constant peril to the ecosystem [31,46]. New oil projects imply new roads that would give access to new human settlements [47], increasing pressure in the rain forest. The same analysis is valid for large hydropower projects [31]. In the last decades, the government improved the road network in most of the country, enhancing the connectivity in the Amazon region, which may speed up the expansion of the agricultural frontier and also the deforestation of the native forest [48].

Additionally, new agro-industrial stakeholders and market requirements can increase the pressure over forest lands. For example, a massive deployment of biofuels or monocultures would require land-use changes, most likely with the expansion of the agricultural frontier. Thus, land devoted to agricultural activities, including those for energy purposes, must follow adequate management practices to reduce deforestation [49,50].

4. Methodology

Ecuador Land Use and Energy Network Analysis model (ELENA) was created in the context of the Deep Decarbonisation Pathways in Latin America and the Caribbean (DDP-LAC) project. This project seeks to improve the modelling capacity of the academic community in LAC countries to develop and use IAMs. During this endeavour, a team from the Escuela Politécnica Nacional (EPN) was advised by the Cenergia Lab from the Graduate School of Engineering, Universidade Federal do Rio de Janeiro (UFRJ/COPPE) to develop the ELENA model from scratch. To the authors knowledge ELENA is the first IAM for Ecuador. The model is built following the methods and framework of the Brazilian BLUES model [13,52], and uses outputs from the COFFEE global model [17], both applications of the MESSAGE platform. However, BLUES, COFFEE and ELENA, contain their own modelling structure, set of constraints and specific datasets, corresponding to the individual realities they represent, which make them unique in their own way.

4.1. MESSAGE platform and the BLUES and COFFEE models

The MESSAGE platform, developed by the International Institute of Applied Systems Analysis (IIASA), is a mixed-integer and linear programming model, with a perfect foresight optimization platform.[3] It is designed to evaluate different strategies of suppy development to meet a given demand in competitive market conditions [53]. This tool allows for the development of IAMs that combine techo-economic and environmental variables to generate cost-optimal solutions. Originally built for the energy system, it minimizes the total cost of expanding and operating the energy system to meet energy service demands. Constraints are used to represent real-world restrictions to explore the full range of the variables [54]. Such restrictions include, for example, the total amount of GHG emissions, availability of resources, activity and

[3] MESSAGE is the platform where the ELENA model is built. IIASA also calls their application in the platform as MESSAGE, being MESSAGE-IIASA, then, the model developed in the MESSAGE platform.

capacity of processes, international trades, environmental regulations, investment limitations, availability and price of fuels, market penetration rates of new technologies, among others [13]. Techno-economic input parameters considered include specific investment costs, operation and maintenance (O&M) cost, construction times, life span, process conversion efficiency, GHG emission factor by process, and any technical or economic specifications that may be required to appropriately model the performance and expansion of an energy technology [54]. The generic version of the objective function and main restrictions used by MESSAGE are presented in Appendix A 1.

Since 2003, the Brazilian team at Cenergia Lab (UFRJ/COPPE) has gained much experience using MESSAGE, applied at a national and global level. Several studies have been carried out for Brazil with the MESSAGE-base models [5,37,53–61,63]. The last version of the national MESSAGE-Brazil[4] is the so-called Brazilian Land Use and Energy System (BLUES) [37,60,62,64]. The BLUES model is a novel application of the MESSAGE platform adapted to promote the integration of the land-use system into the energy system [17,52], in a hard-link approach. Different types of land covers can be converted into each other while accounting the particular GHG emissions (CO_2, CH_4 and N_2O) resulting from this process. Also, a certain type of land covers can be used for agricultural production, in order to meet food and energy demand. Furthermore, agricultural products can be traded between regions. BLUES minimizes the cost of the expansion of the entire energy and land systems, subject to fulfil energy and new additional land-use restrictions. The additional main equations to incorporate the modelling of the land use system in BLUES are presented in Appendix A 1. At the global level, the COFFEE integrated model was developed in the MESSAGE platform to provide long-term (up to 2100) assessments of the interaction between the energy and land-use systems and the economy at the global scale. COFFEE works with a similar approach to the BLUES model. A detailed description of COFFEE is shown in Refs. [16,17].

4.2. ELENA - Ecuador land use and Energy Network Analysis model

The ELENA model is an application of the MESSAGE platform, using the methods and framework of the BLUES model [13], applied to Ecuador. ELENA considers four regions: Coast, Andes, Amazon and Galápagos.[5] The base year is 2015, the time horizon is2050,[6] and it uses 5-year time steps. Each modelling year has a seasonality of 12 months, and for each month there is a typical day. Each day is divided in five time slices (night, morning, PV peak, day and load peak) defined to appropriately model the behaviour of variable renewable resources and electricity demand. The ELENA model considers six economic sectors (transportation, residential, commercial, industry, agriculture and others). The industrial sector is disaggregated in nine subsectors: food and beverage, textile, wood and paper, steel, mining, non-ferrous, chemicals, non-metals, and others. The general structure of ELENA model is presented in Fig. 4.

The model must satisfy the primary constraint, which is meeting the demands allocated to each sector. In addition to that, the model works under a set of assumptions that build a scenario, providing different results at each case. These scenarios are not meant to predict the future, but to represents hypothetical realities that would be reached by varying the assumptions that govern the model. In this sense, the model is able to evaluate policies by implementing certain constraints (e.g. effects of a reforestation policy).[7] The useful energy demand is calculated exogenously. The main drivers used to forecast the demand growth were GDP [65] and population [66] depicted in Fig. 5. Sectorial GDPs were also used to improve sectoral energy demand projections.

Transport demand is divided into passenger (pkm) and freight (tkm). The main driver to forecast the passenger demand is population evolution. Assumptions in mileage and vehicle load capacity evolution framed the transport demand; details are presented in Table 2. Passenger transport is classified into individual vehicles and buses. Regarding freight demand projection, the main driver is the GPD, and three truck categories (light, medium and heavy) are considered.

The useful demand in the industrial subsectors is divided in four categories: steam, direct heat, drive and others. The main drivers for industry demand are the sectorial GDP and the specific energy consumption by physical production.

Household (HH) energy service demand was calculated in a bottom-up approach that includes population, HH size evolution and specific consumption per HH. A distinction between existing and new HH allows assessing improvements in energy efficiency, by considering improved technologies in new HH. Energy services for HH include refrigeration, air-cooling, lighting, water heating, cooking and appliances.

Commercial and Agriculture & Others energy demand are built using the sectorial GDP. For the commercial sector, the energy services are separated between electric appliances and others, while for Agriculture and Others the demand was estimated in terms of final energy.

In Fig. 6, energy inputs and outputs for the different sectors modelled in ELENA are presented. Appendix A 4 across multiple tables shows the most important technical and economic considerations in ELENA model. The sectoral energy service demand up to 2050 is presented in Table A- 4 and Table A- 5. The set of technologies considered in the power sector is presented in Table A-6 (including thermal plants with carbon capture and storage (CCS)). Table A- 7 presents the details to model hydro power plants. Finally, Table A- 8 presents the set of technologies considered in the transport sector.

The land-use modelling considers three regions (Coast, Andes and Amazon). The Ecuadorian land cover map, which has 16 classes [67,68], was geoprocessed in Arcgis to create a new map with eight aggregated land cover types: forest, protected forest, planted forest, grassland, protected grassland,[8] pasture, cropland and others. Edaphoclimatic conditions data from GAEZ/IIASA [69] was processed to generate an area-weighted average crop suitability index (CSI) map for Ecuador. This average CSI map was calculated considering the specific CSI of the 11 most essential crops [70] in the country that accounts for 85% of the planted area. Detailed information about the data used to produce the national CSI map is shown in Appendix A- 3. Additionally, the travel time to main cities was used to consider the preference for using first the land closest to the main population centres. The global map of accessibility to high-density urban centres for 2015 [71] was used. As a next step, the travel time and CSI rasters were reclassified into seven relative cost classes as detailed in Ref. [52].[9] Then the average CSI and travel time rasters containing the relative values were multiplied. This procedure resulted in 56 relative production cost classes. In order to improve computational performance, these are aggregated into seven

[4] The name of the application of the MESSAGE platform to Brazil developed at Cenergia Lab, at COPPE/UFRJ, has changed over time. The most recent version of MESSAGE-Brazil is called BLUES.

[5] Galápagos region exist in the model architecture, nevertheless in this model version this region is not being used. All energy demands from this region are included in the Coast region.

[6] Optimization runs up to 2055, results are shown up to 2050.

[7] In the present work, six scenarios were modelled; detailed information of the scenarios is presented in section 2.3.

[8] Protected grasslands are mostly moorlands called "páramo" in Ecuador.

[9] Actually, the amount of 7 classes is an arbitrary number to regroup the 56 original categories. Since the MESSAGE platform was not originally built for integrating land use and energy in the same tool, in ELENA the energy equations were adapted for land use. This creates a large number of equations and increases the modelling time resolution. Therefore, we decided to aggregate the classes onto 7 to reduce the number of equations and decrease computational time, without losing the needed information required by the model.

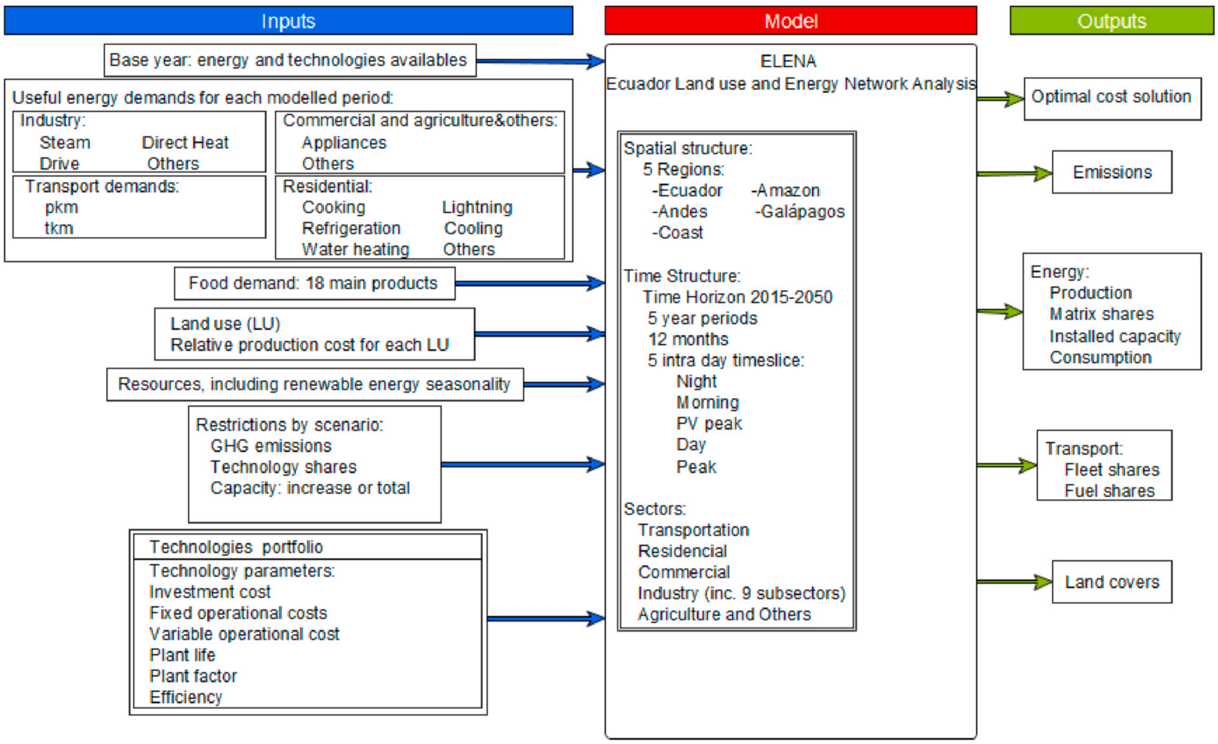

Fig. 4. ELENA model structure, inputs and outputs.

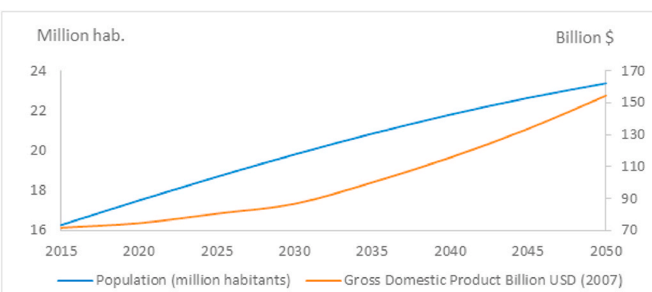

Fig. 5. Main drivers: GDP and population forecast to 2050 [65,66].

cost classes in the ELENA model (See Fig. 7). Cost classes are identified with letters, from A to G, representing A the lowest production cost and G the highest. As the last step, the information on agricultural production costs was disaggregated by region. ELENA considers this relative production cost class data to decide the land-use changes by the period under the least cost criteria to supply energy and food demands, subject to restrictions (e.g. reforestation and deforestation scenarios).

Fig. 8 shows the land use conversion possibilities in ELENA model. Protected forest and grasslands areas can be accounted for in ELENA by constraining the minimum area subject to land-use change for each category. This establishes a minimum threshold that is therefore protected and not influenced by the pressure of agricultural expansion.

For every time step, national food production is calculated by adding total national consumption and exports and excluding food imports. Food imports and exports forecast are determined by means of a linear projection of historic values obtained from FAOSTAT [72]. From the FAO database, 18 categories containing relevant agricultural products for Ecuador are considered (See Appendix A-2). The food supply projection is calculated to account for dietary changes and food waste [73] evolution, which is important in decarbonisation scenarios. Food supply projection is driven by population growth and an increased caloric content diet that would reach current developed countries food intake levels until 2050. The annual demand (metric-tons) of a certain product is calculated by multiplying the share of the product in the daily diet, the daily diet (kcal/day/person), population, 365 days, the inverse of the percentage for its food waste, and an appropriate conversion factor [73].

4.3. Scenarios description

Six different scenarios are evaluated, in order to assess the impact of energy, land and environmental policies in the ELENA model. Each scenario is constructed with a specific storyline, which affects a set of assumptions on input data, such as those relevant for demand projection and determining technological perspectives. Public policies are implemented by applying specific constraints, being the carbon budget an example of that. These scenarios are described in Table 1.

Scenarios must be endorsed with a narrative that connects them with a possible future reality. The narratives considered in the present work are based on the results of the Laboratory of Energy Transition in Ecuador [74] following the methodology of [75]. This project lasted for three years, in which ideas of interdisciplinary stakeholders of the energy sector were combined to build transition scenarios for Ecuador. Nevertheless, these narratives contained qualitative storylines that had to be transformed into quantitative data to be implemented in ELENA. This quantitative data shapes the model in the form of demands, restrictions, or technological parameters (e.g. efficiency changes over time). One of the main constraints used to shape the DDP scenarios was the national carbon budget, limiting cumulative CO_2 emissions from 2010 to 2050. This carbon budget is specific for Ecuador and it was calculated based on the South America region's carbon budget, defined by the global COFFEE model [17]. That carbon budget was distributed to South American countries based on the GDP per capita[10] proxy. Due to uncertainties in the global carbon budgets calculations, there is an

[10] Several exercises were done to distribute the South America carbon budget by country: by total GDP, population, GDP per capita, etc. We took the most restrictive budget, which is based on the GDP per capita relation.

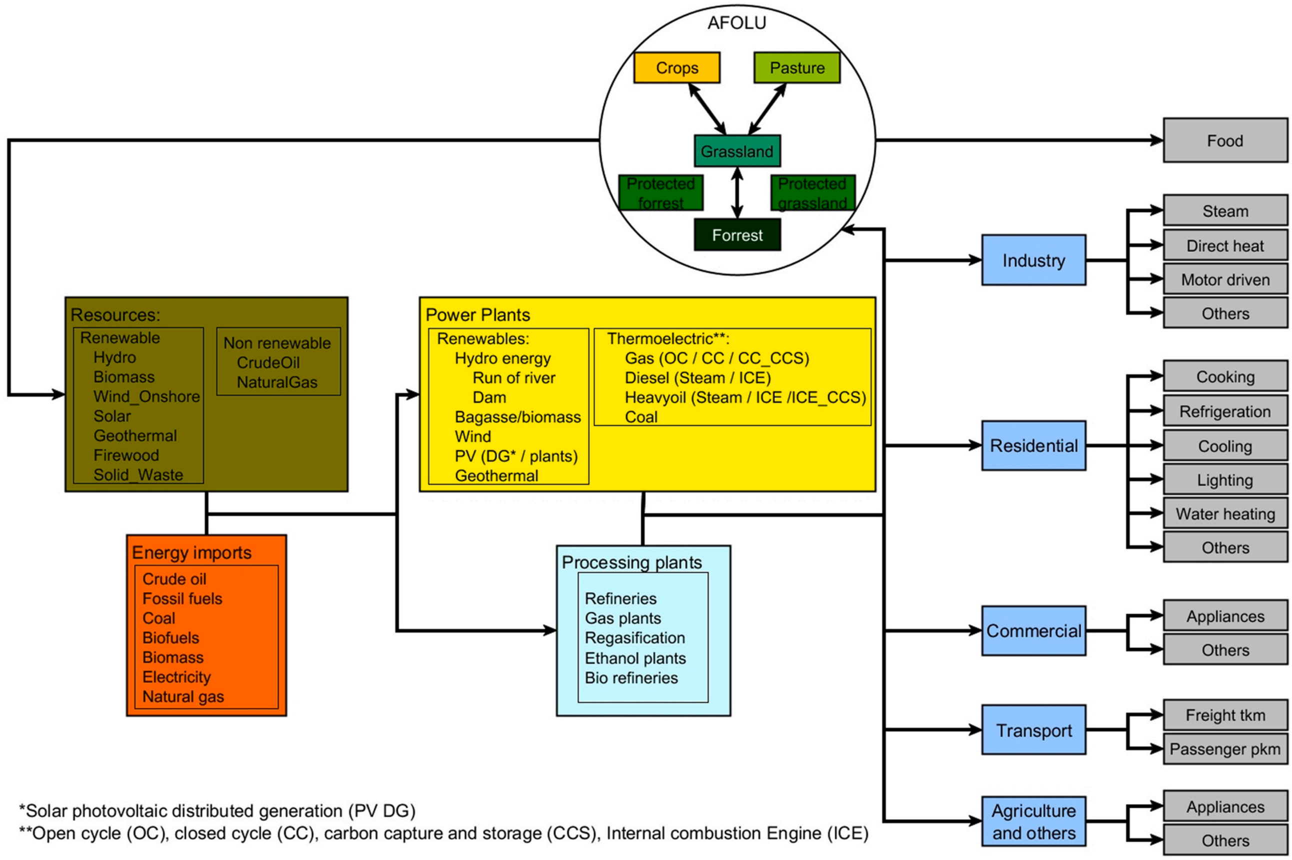

Fig. 6. Representation of the energy and land use system conversion chain in the ELENA model.

interval for the decarbonisation levels corresponding to a global limiting temperature of 1.5 °C. Thus, this study assumes that the value of 1.46 $GtCO_2$ represents a well below 2 °C target, whilst the 1.25 $GtCO_2$ represents the strictest 1.5 °C limit. Table 2 presents the main assumptions of all scenarios, and a detailed description of each scenario is presented in Appendix A 5. Table A- 8 presents the evolution of the values of many parameters and the premises in each scenario in the period 2015–2050.

4.4. Data

Official data from government entities were considered when available. The National Energy Balance from different years [29,39,40] was used for general energy information and trends. For the transport sector, there is available a complete compendium of fleet evolution for passenger and freight [76] Nevertheless, the are a few national statistics related to transport activity. Thus ICCT[11] and COFFEE data were used to have some detailed parameters [17,77]. In the electric power sector, high-quality data with information of powerplants, from prefactibility projects [78] to operational statistics [79], is available.

Moreover, electric power load curves were used to define the intraday time periods for Ecuador, which was implemented in ELENA. For renewable sources, comprehensive studies of wind resource measurements [80] and residues availability [81] were used. In the case of solar resources, simulations using the System Advisor Model (SAM), which uses the information of the National Renewable Energy Laboratory (NREL) [82], allowed to determine the global horizontal irradiance. A major challenge was to determine the final energy use for the industrial sector. At first, the overall final energy consumed was obtained from the National Energy Balance report [40]. Then, it was attributed to the industrial production, using the reports of companies, which led to the specific energy required by metric-ton of product [83–85]. Finally, since the input variable into ELENA is useful energy, energy conversion efficiencies were defined considering different processes and fuels. For the AFOLU sector, a variety of data was collected. In order to set the base year, crops' yield and livestock densities were required [86]. Historical averages for reforestation and deforestation from 1990 were analysed to create the required model constraints. As explained before, the mapping of different crops were created to analyse the land-use change. To determine the food production demand, FAO database was considered [72]. Besides, as explained before, geoprocessed data in Arcgis and Edaphoclimatic conditions data were used to create the land use category classes that determine land use interactions.

In order to project the data through the entire studied period, different techniques were applied. In the residential and commercial sector, a bottom-up approach was developed using demographic parameters. For the transport sector, a dashboard created by IDDRI at the DDP project was used considering the different goals for each scenario [87]. For the industrial sector, the projection was driven by the GDP, with adjustments made according to induced changes on efficiency considering figures from developed countries taken from the RETScreen database [88].

Regarding food production, the FAO database provides a historical tendency for agricultural production. It was linearly extrapolated, maintaining a coherence between the increase in productivity and the limits for the crop yield improvements. In addition, food losses [73] and dietary parameters were included in the calculations, which allowed to perform variations in dietary tendencies and include its effects on the food demand. The food projections considered a dietary intake as the base for the calculations, allowing to reach developed countries dietary level.

[11] ICCT=International Council of Clean Transport.

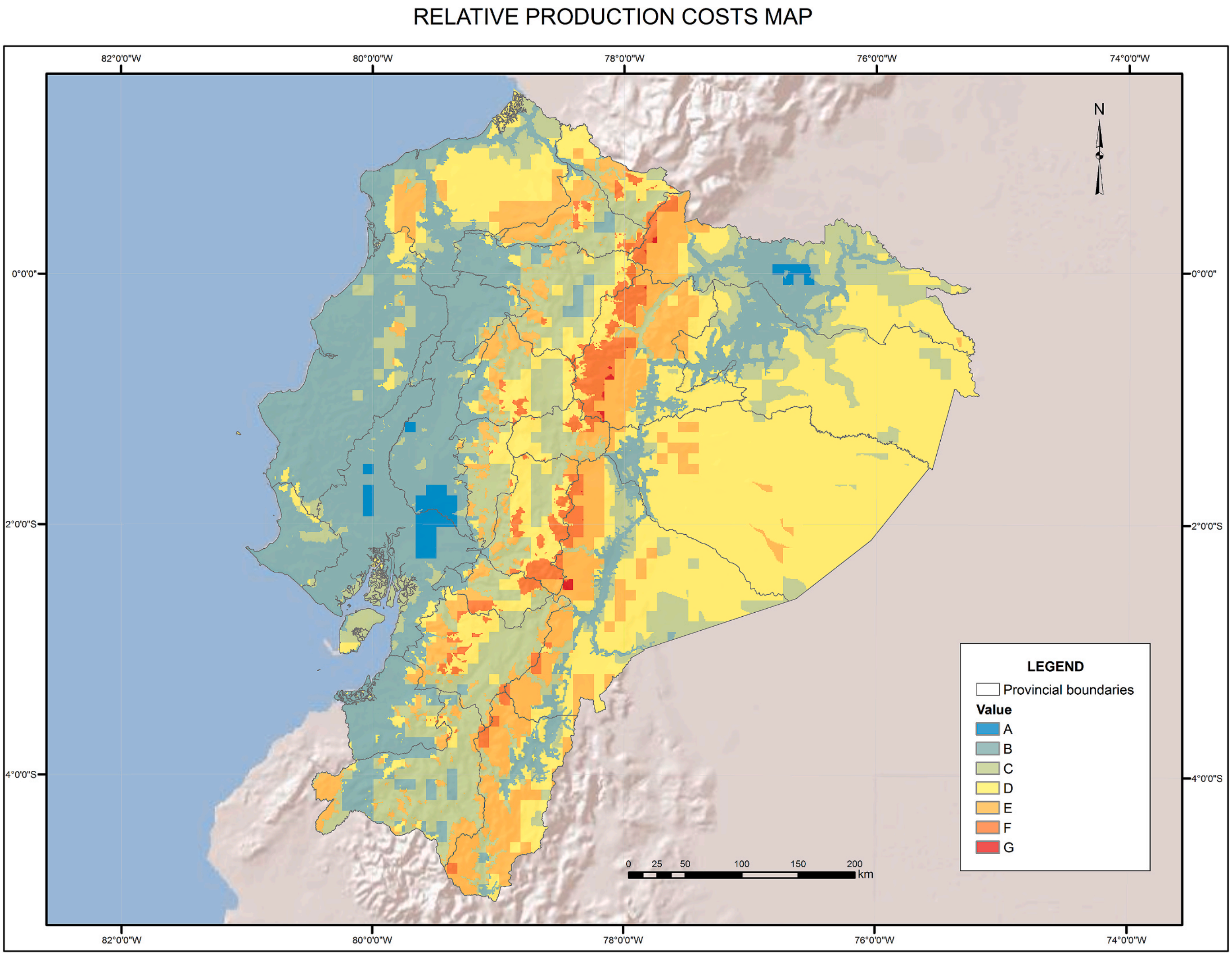

Fig. 7. Relative agricultural production cost map for Ecuador.

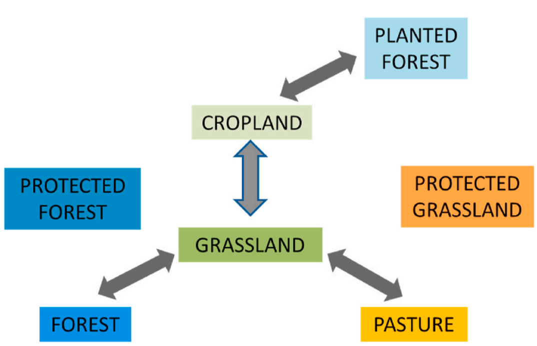

Fig. 8. Land use conversion possibilities in ELENA model.

5. Results

Results for MinC, DDP_{High}, DDP_{Low}, DDP_{High_Refo} scenarios are present in this section. Analysis of the NDC scenarios is only considered while comparing the emissions level to picture the different decarbonisation trajectories. Despite the results available for all scenarios, the comparison between the MinC and the DDP scenarios is prioritized.

In the MinC scenario, it is expected a slight diversification of the primary energy matrix in the coming decades, due to an increase of non-conventional renewable energies (Fig. 9). Nevertheless, primary energy would remain based on, roughly, 80% of fossil fuels. Oil dependence for Ecuador will continue, despite the local production reduction. Under the MinC scenario, Ecuador becomes a net oil importer by 2045. This is an energy problem and an economic issue, as well, as discussed previously. Historically, coal is not part of Ecuador's energy matrix, but there is no prohibition for its usage. Without GHG emission constrains, results in the MinC scenario show an increase of coal use, since imported coal would be a cheap source for the electric power sector expansion.

In all DDP scenarios, the highest increase occurs in bioenergy. By 2050 biomass contribute with around 700 PJ becoming even more important than oil, which contributes less than 400 PJ in the primary energy supply. Oil trade deficits and, hence, Ecuadorian oil vulnerability, a major issue in the MinC scenario, is controlled in the DDP scenario, by means of liquid fuel switches. In 2050, half of domestic supply primary energy is supplied by advanced bioenergy, while fossil energy represents 41%, and other renewable energy represents the rest.

A counter-intuitive finding is the higher increase of primary energy supply by 2050 in the scenario with higher carbon restrictions (DDP_{Low}). This occurs because biomass is commonly applied in less efficient processes, which results in higher primary energy demand. Alternatively, in the DDP_{High_Refo} scenario, where GHG emissions are mitigated mainly by means of reforestation, reducing the role of bioenergy, the primary energy supply decreases by 2050, relative to MinC.

Electricity demand continuously grows in the coming years, as

Table 1
Scenarios modelled with ELENA.

Commitment level	Scenario Name	Description
Reference scenario	Minimum Cost* (MinC)	This is a reference scenario that maintains the policies that are in place and the ones already stablished to come in a near future. No carbon restriction is applied.
Government engagement scenarios	Unconditional (NDCu)	This is a scenario containing the National Determined Contributions policies that Ecuador is committed to achieve by itself.
	Conditional NDC (NDCc)	This scenario contains the National Determined Contributions policies that Ecuador is committed to achieve with financial and technical support from the international community.
Deep decarbonisation (Disruptive scenarios)	DDP $_{High}$	This scenario is restricted by a cumulative carbon budget of 1.46 Gt CO_2 for the period 2010–2050. It is aligned with a well below 2 °C limiting temperature.
	DDP $_{Low}$	Similar to scenario DDP_{High} but with a carbon budget of 1.25 Gt CO_2 aligned with a 1.5 °C limiting temperature.
	DDP $_{High\_Refo}$	This scenario has the same carbon budget that DDP_{High} but includes a constraint simulating a reforestation policy.

Note: * Although all the scenarios are optimized under the vision of minimum total cost, subject to restrictions, the MinC scenario uses few restrictions, so that ELENA optimizes more freely.

Table 2
Scenario main assumptions.

Sector	Parameters	MinC	NDCu	NDCc	DDP[a]
		(compared to base year)	(compared to MinC scenario)		
Transport	Private mobility share	Increase 36%	"	"	Reduced 60%
	Average travel distance (cars)	Increase 13%	"	"	Reduced 25%
	Share of EV in fleet	Increase	"	Increase	Increase
	Occupancy	1.7 people/car	"	"	Increase 6%
	Tonnage rate	20 people/bus	"	"	Increase 25%
	Motorized demand in Gpkm	134	"	"	121
	Demand in Gtkm	75.9	"	"	75.9
Industry	Production's energy intensity	2% reduction	Reduction in cement	14% reduction	14% reduction
	Use of Bio-energies	15% in food&beverage industry		"	Up to 10% increase in cement ind.
Residential	Electric shower share	65%	"	"	78%
	Induction stoves share in urban areas	11.5%	"	30%	50%
Power plants (installed capacity)	Hidro	6.2 GW	"	8.6 GW	8.6 GW
	Thermal	3.5 GW	"	"	"
AFOLU	deforestation rates (ha/year)	108 000	3% reduction	12% reduction	94% redution
	reforestation rate (ha/year)	31000	None constraint used	None constraint used	2.6 times increase[b].
Food production	Diet (Kcal/cap/day)	42% Increase	"	"	50% meat replaced by soy
	Food waste	Same as base year	"	"	50% reduction

[a] Between DDP scenarios, the carbon budget and the reforestation policies are the only variants.
[b] This value represents the reforestation policy used only in the DDPHigh Refo scenario. Quote mark (") is used when the parameter of the MinC scenario is maintained.

shown in Fig. 10. In the MinC scenario, coal power plants will be used to supply the additional demand in the future. It is one of the least-cost options especially for the Coast region, due to its increased international trade and access at seaports. By 2050, 30% of the electricity is produced from coal, 40% from hydropower and the rest is mainly non-conventional renewables.

On the contrary, with carbon restrictions in place, a massive deploy of coal technology is no longer an option for the power sector. Thus, in the DDP $_{High}$ and DDP $_{Low}$ scenarios, biomass electricity generation equipped with CCS develops faster (BECCS[12]), supplying around 30% of the electricity from 2035. Mostly woody biomass would be used to produce electricity. For these scenarios, hydropower represents the base of the electric generation, maintaining a stable electricity production until 2045, and increasing it in around 30% only in the last periods.

Finally, the scenario accounting for reforestation policies (DDP_{High_Refo}) does not rely heavily on energy crops and thermal biomass power plants with CCS as much as the other DDP scenarios. The DDP_{High_Refo} scenario shows a minor share for BECCS, 12% by 2050, while hydropower almost doubled its production in the last three periods.

Fig. 11 shows the evolution of installed capacity in the electricity sector. Hydropower is the dominant technology in all scenarios, but its share in the electricity generation reduces in the coming years, due to the expansion of other sources. There is an increased capacity in solar PV systems, both distributed systems and utility-scale plants. In the MinC scenario, the expansion of PV systems is the most prominent, followed by coal. In the DDP_{High} and DDP_{Low} scenarios, biomass and solar PV increase similarly, while coal is used in a small share and only equipped with CCS. In the DDP_{High_Refo}, biomass capacity expansion is less important than that of the former DDP scenarios, while hydropower share represents more than half of the installed capacity. In all scenarios, natural gas fuelled-thermal power plant capacity increases in the mid-term but then decreases. Thus, it acts as a transition technology.

Fig. 12 shows GHG emissions decomposed by sector. As expected, GHG emissions increase in the MinC scenario. AFOLU sector is the main contributor at first, but then it is overtaken by the increase in the transport sector.

On the contrary, DDP scenarios indicate an increasing trend towards negative CO_2 emissions in the energy sector, due to the large amount of BECCS deployed. In the DDP_{Low} scenario, the stricter carbon budget requires even higher use of negative emission technologies. However, DDP_{High_Refo} scenario presents a decrease in the need for negative CO_2 emissions from the energy sector, due to increased negative emission from the land sector. Thus, negative emissions options consistently play an essential role in all DDP trajectories.

[12] BECCS means "Bioenergy Carbon Capture and Storage".

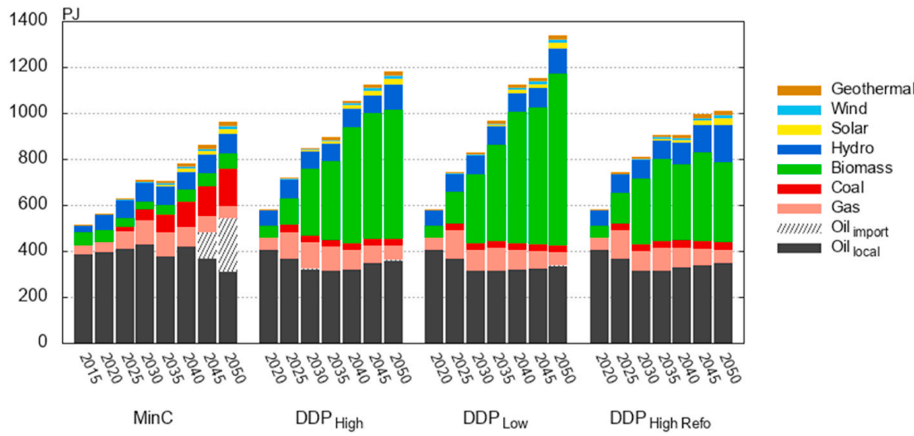

Fig. 9. Primary energy supply.

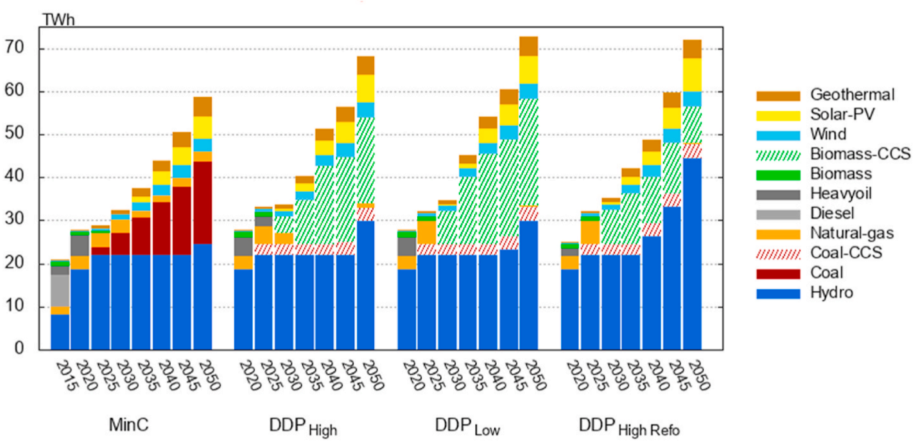

Fig. 10. Electric generation.

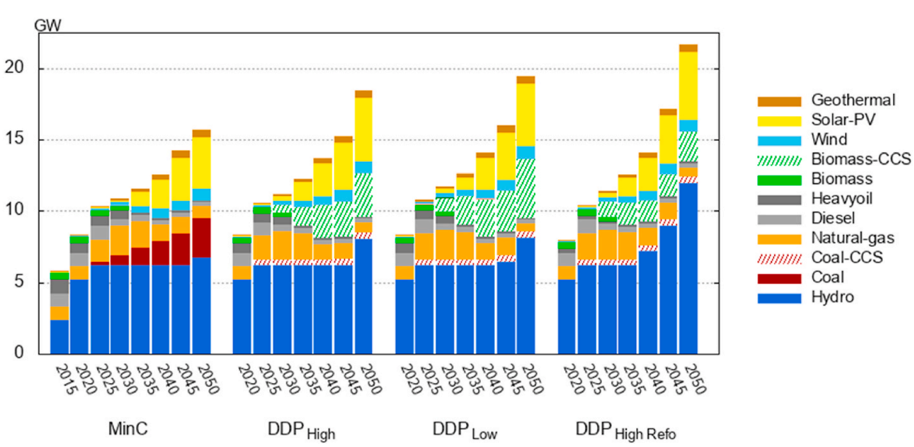

Fig. 11. Power installed capacity.

The reduction of transport sector emissions in the DDP scenarios is mainly explained by activity effects, as individual mobility reduces more than 50% in 2050 compared to 2020, and structural effects, due to the increasing use of public modes of transport (See Fig. 13, Fig. 14 and Fig. 15). Moreover, conventional fuels such as gasoline and diesel are replaced by advanced biofuels, natural gas and electricity. Notably, electric vehicles play an important role for both individual and public transport. Electric light-duty vehicles also play a role in the decarbonisation of freight transport (Fig. 16).

Fig. 17 represents the emissions per year for different scenarios. NDCs and MinC scenarios follow a similar trend. This confirms that the policies implemented in the Ecuadorian NDCs consider only a short-term strategy. Without new policies in place for the long-term, from 2030 the model optimizes the system seeking for the least-cost configuration. Therefore, emissions constrained in the short-term under the NDC strategy start to grow again. Even if there is a reduction in cumulative GHG emissions, it is clear that the NDCs trajectories are not in line with the goals of the Paris Agreement.

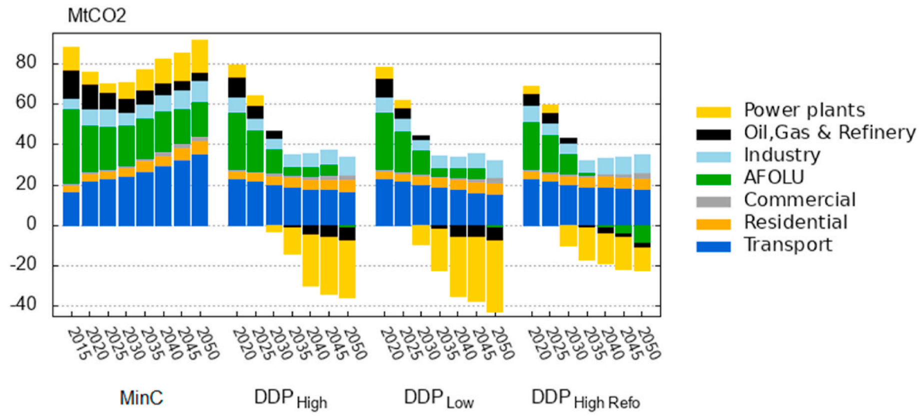

Fig. 12. GHG emissions, by sector.

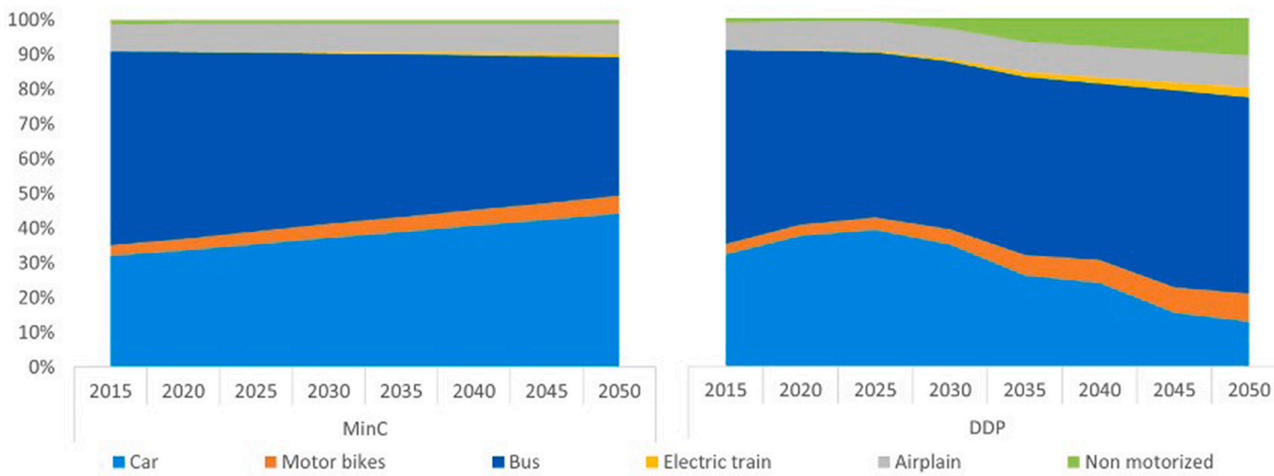

Fig. 13. Modal share evolution for passenger transport in MinC and DDP scenarios.

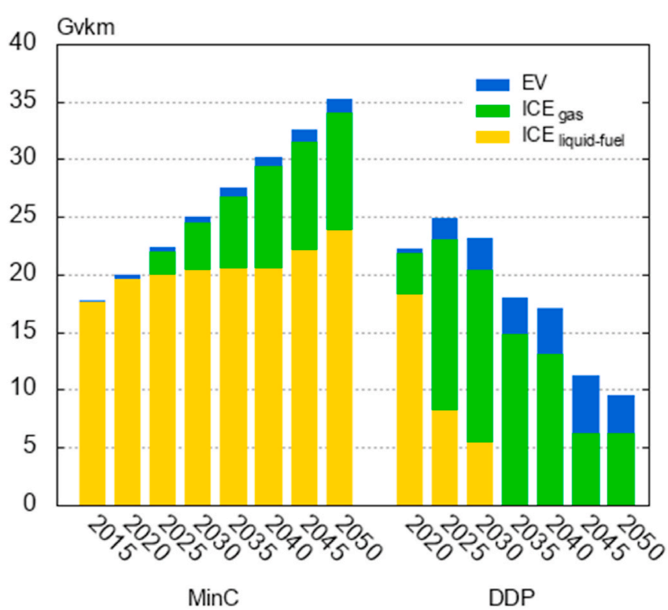

Fig. 14. Individual vehicles mobility for cars by fuel (vkm).

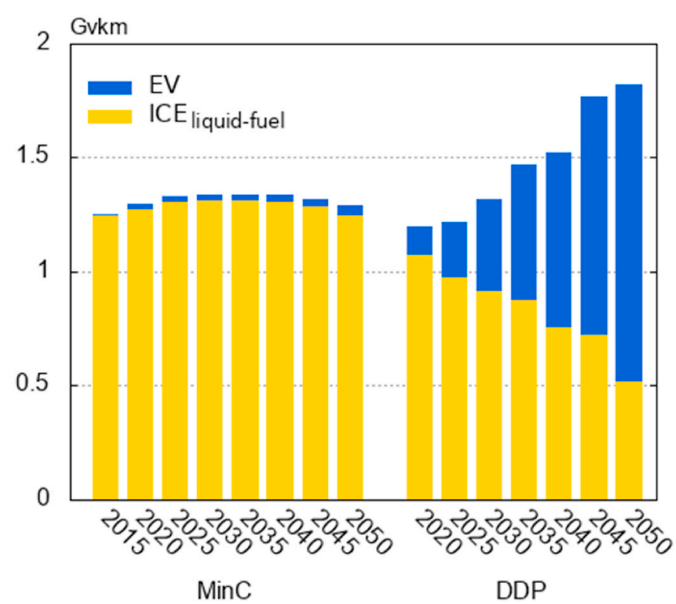

Fig. 15. Public transport mobility for bus by fuel (vkm).

On the contrary, the DDP scenarios demonstrate different decarbonisation pathways, compatible with a well below 2 °C and a 1.5 °C scenarios. For scenarios DDP $_{High}$ and DDP $_{Low}$, emissions decrease constantly until 2040 when the GHG emissions decline decelerates and the curve starts to flatten. DDP $_{High\ Refo}$ scenario shows decreasing

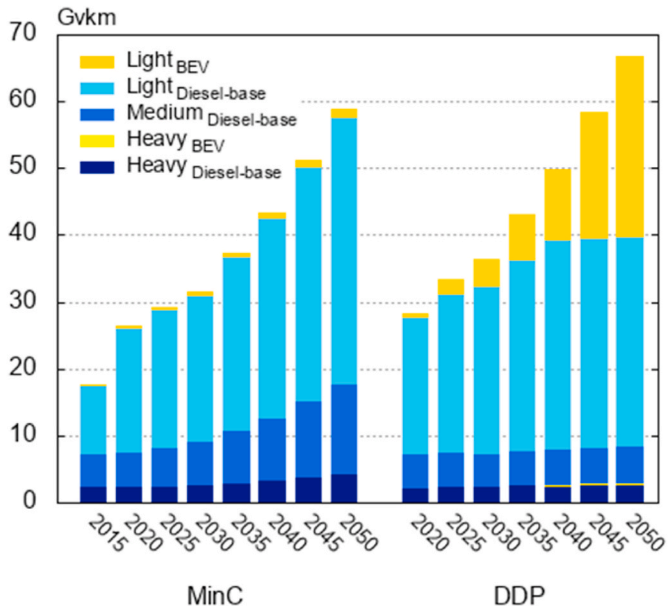

Fig. 16. Freight transport mobility for trucks by fuel (vkm).

emissions up to 2040 when its emissions level remains stable. The most restrictive carbon budget of the DDP $_{Low}$ scenario achieves the lowest annual emissions from 2030 onwards. Results show that, until 2050, Ecuador does not need to be carbon neutral to comply with the 1.5 °C global target.

Fig. 18 describes the evolution of cumulative land-use changes with respect to the base year. In a MinC scenario, deforestation increases, resulting in increased areas of pastures and grasslands. In the DDP (High and Low) scenarios, forest area is maintained after 2030. Only in DDP $_{High\ Refo}$ there is a positive forest balance in 2050, meaning that there is more forest area in 2050 than there were in 2015 due to reforestation policies. The DDP $_{High}$ and DDP $_{Low}$ show an increase in croplands, as planted forest for woody biomass are also considered in that category.

6. Discussion

The deep decarbonisation pathways, DDP_{High} and DDP_{Low}, going from a "well below" 2 °C to a 1.5 °C target, represents a variation on the national carbon budget of around 15% when compared to each other. These scenarios' results, with respect to energy, land use and emissions, do not change substantially amongst themselves. This gives certain robustness to the results and provides a clear path to policymakers. On the other hand, they differ considerably from both MinC and DDP_{High_Refo}.

Findings indicate that crude oil (local or imported) remains an important energy source in Ecuador for the coming decades, regardless of the scenario. In a GHG emission mitigation context, this means that the emissions provided by fossil fuels must be compensated. Biomass-related technologies compose the leading solution to this challenge, not only as a renewable source for thermal power plants and biofuels, but also associated with CCS. It results both in negative emissions in the energy sector and in a fast increase of biomass as primary energy, in DDP_{High} and DDP_{Low} scenarios. This happens even counting for direct and indirect land-use change emissions (as ELENA is able to account for both). Nevertheless, this stark biomass energy conversion ramp-up is smoothed in the DDP scenario that simulates an aggressive reforestation policy (DDP_{High_Refo}), since the forest itself would be a natural carbon sink. A large portion of the biomass energy conversion happens in thermal power plants equipped with carbon capture and storage systems, although an afforestation scenario such as the $DDP_{High\ Refo}$ scenario proves to be much less dependent on BECCS.

This is a crucial result since it shows that BECCS is used to compensate for GHG emissions produced in other sectors. Therefore, a common issue of all ambitious DDP scenarios refers to BECCS feasibility in Ecuador. Actually, BECCS feasibility is a major issue for every country in the world as acknowledged in Refs. [89,90], even in countries with a large record on converting biomass to energy carriers [13]. Except for the very specific case of CO_2 capture from process emissions in ethanol production (which is easier than the capture from flue gas of combustion processes), the CO_2 capture at large scale in biomass energy conversion facilities is not yet fully mature nor deployed. From the 19 large-scale carbon capture facilities operating in the world in 2019, the majority refers to natural gas processing plants (also easier capture processes than combustion ones), and there is only one BECCS plant operating, and, as expected, capturing CO2 from ethanol fermentation in the USA [91].

It is somehow a vicious cycle: without extensive and permanent near-term reductions in the world energy demand, scenarios that aim to cope with the "well-below 2.0-degree target" need negative emission technologies (NETs), particularly BECCS, to be feasible [92,93]. However, at the same time BECCS, beyond the option related to ethanol fermentation, can only become a viable option at large-scale after passing through a learning curve starting from now. Interestingly enough, this was already acknowledged by Ref. [94] for all CCS facilities (biomass and fossil fuel ones), who notes that GHG mitigation emission policies lead to a type of system inertia, where decision-makers simultaneously

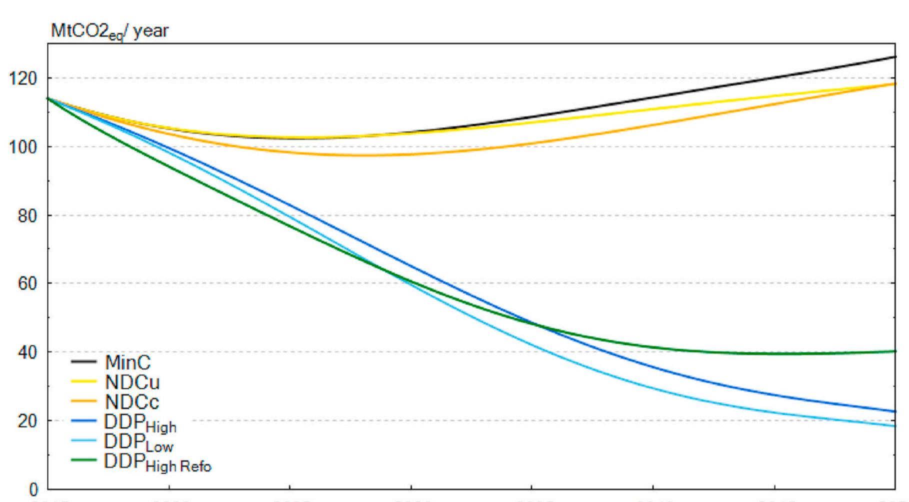

Fig. 17. Total annual national emissions, by scenario ($MtCO_2$eq).

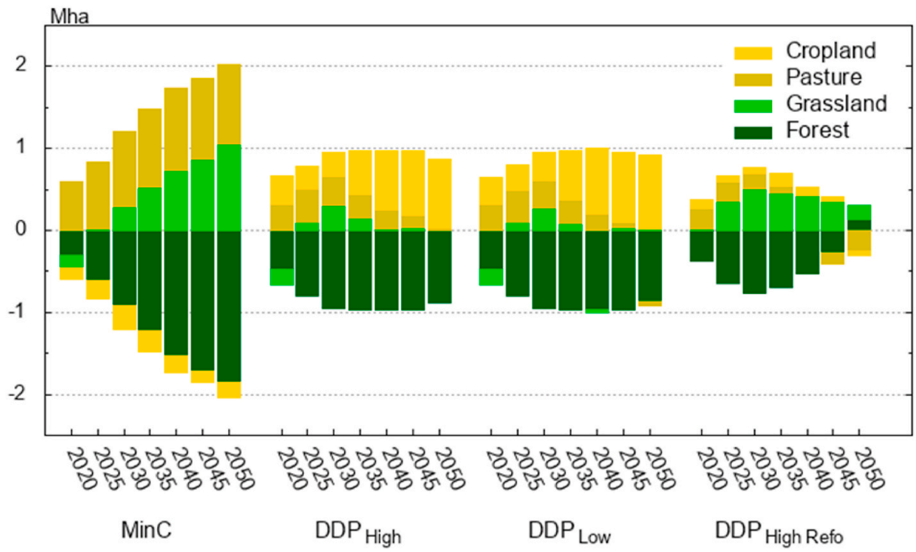

Fig. 18. Cumulative land use change (relative to base year).

affirm that the cost of CCS technologies is high, which makes current investment difficult, but that these technologies are promising, so their cost will be reduced by technological learning. In other words, the current investment in CCS does not occur, because it is high, but at the same time, the prospect of reducing the cost of CCS options in the future is affirmed, which will hardly occur without the current investment. In the end, should countries follow a DDP strategy, all will need to join efforts and share results to be able to allow a spread and large-scale deployment of BECCS, particularly in countries were biomass energy conversion is or can become relevant [95]. Possibly this will also depend on a boost on climate finance for supporting BECCs deployment in emerging countries [96].

In the end, a central discussion that arises is the trade-off observed between BECCS and forest as emissions reduction strategies in Ecuador, as it was observed in other South American countries where LUC emissions are relevant [13]. By running the ELENA model, it was possible to carry out this trade-off analysis between two decarbonisation scenarios. Being it a game changer situation, further studies should deepen this discussion. For example, a reforestation program must account for the economic benefit that the forest delivers. Forest ecosystem services, provide resources, regulates cycles (in water, soil and weather) and encompasses cultural services [97]. All these benefits must be included from an economic perspective to better evaluate the $DDP_{High\ Refo}$ scenario, while the DDP scenarios relying on BECCS should account for its advantages (e.g. oil substitution, labour and income creation) and risks (not yet mature and regulated high-cost option).

7. Conclusions

The decarbonisation of a country could be achieved according to several different strategies. Nonetheless, it should be consistent in terms of avoiding leakages between sectors and sub-optimal solutions. One advantage of building and running a national integrated assessment model (IAM) is to perform this task, particularly in tools prepared to handle the detailed modelling of land and energy systems simultaneously. The Ecuador Land Use and Energy Network Analysis (ELENA) model was prepared under the aegis of the project “Deep Decarbonisation Pathways Project for Latin America and the Caribbean (DDP-LAC)” precisely for that purpose. This paper presented decarbonisation scenarios developed with ELENA but sets up a tool able to explore many other scenarios and detailed sectoral analysis. Accordingly, the modelling procedure applied in Ecuador (from a matrix firstly created in Brazil) could be well reproduced in other countries that share similarities (relevant emissions from Land Use Change (LUC), deforestation issues, the role of the transport sector in GHG emissions, and so on), such as other Latin American countries.

Deep decarbonisation pathways (DDP_{High} and DDP_{Low}) tested in Ecuador present consistent and similar results in terms of technological needs and overall transformative pathways. On the other hand, a notorious change happened when a reforestation policy was modelled in the DDP_{High_Refo} scenario. This scenario highlighted the climate significance of land protection policies, which can have repercussions on the evolution of the energy system. As such, these results provide a clear set of actions needed for policymakers to develop climate policies and long-term energy planning in Ecuador.

Thus ELENA model, the first Ecuadorian IAM, proved to be an appropriated tool to evaluate scenarios and validate policies in a decarbonisation framework.

There is neither perfect model nor a model that does not require a good analyst. The model serves to organize and test assumptions. In turn, ELENA has a limited representation of all economic sectors and, therefore, may not be enough to assess all the socioeconomic and environmental repercussions of each strategy. Nevertheless, the structure of the model allows for the continuous update of the structure and data (such as increasing representation of an individual sector or aggregating other sustainable development issues). Moreover, as is, ELENA already provided insights for Ecuadorian policies, as well as interconnections on the energy and land-use nexus.

Findings show that DDP scenarios are challenging, but do not compromise socio-economic development. The scenarios built in ELENA hold the same premises of Gross Domestic Product and population growth, and the different demands allocated to each sector do not consider any limitations on energy access in order to attain decarbonisation. On the contrary, the DDP scenarios were built over premises that considered modern energy services access similar to those of developed countries. Even when the food demand was estimated (daily food intake), the aim was to emulate the average food intakes of developed countries. In this case, DDP scenarios also considered food waste reductions that could be achieved by public policies. Consequently, the scenarios modelled, far from compromising development, even support a better living condition.

Ecuador is at the edge of a forced energy transition due to imminent petroleum resources depletion. Specific sectors, like transport, will continue to depend mainly on fossil fuels, but it is possible to palliate the effects of a forced transition by starting to design now a future energy matrix. Bioenergy seems to be an excellent candidate to replace oil products (particularly diesel[13]) to some extent. In this case, biorefineries and Bioenergy Carbon Capture and Storage (BECCS) must be studied in the Ecuadorian context. Planted crops may be sustainably managed to provide woody biomass to bio-refineries and thermal power plants. Around 500 thousand hectares of sustainably managed planted forest would be required by 2050. Ambitious reforestation could avoid the dependence on risky and expensive Carbon Capture and Storage (CCS). Reforestation and conservation of an additional 300 thousand hectares, in comparison to the 2015 base year, would provide enough negative emissions to avoid the deployment of an additional 900 MW of BECCS.

Moreover, findings show that increasing electric mobility for passengers and for freight transportation can also pave an energy transition in Ecuador with less GHG emissions and under a less-risky position in terms of oil vulnerability. By 2050, 70% of buses, and 33% of private cars would run electric. Besides, around 10% of passenger transportation demand would be supplied by non-motorized options (walking, biking, skates and skateboards) in urban cities. For freight, by 2050 40% of light and medium trucks and 10% of heavy trucks could be electrified.

As the country has already an electric power system relying on hydro, and there remains a deployment potential for new renewable electricity generation sources, adequate long-term strategies smooth down the effects of the energy transition, by responding to the electricity demand increase, which duplicates by 2050.

Finally, ELENA is a suitable tool to follow and assess Ecuador's National Determined Contribution (NDC) initiative. Findings of this study show that the country's NDCs are not yet aligned with a deep decarbonisation pathway. Indeed, Ecuadorian NDC has to increase its level of commitment to be aligned with the Paris agreement and the well-below 2 °C temperature limit. A long-term strategy is ideal to guarantee that the new NDCs are aligned with a deep decarbonisation goal designed with ELENA. Moreover, a long-term strategy could also be useful to avoid negative externalities that might arise from a trend-based scenario where petroleum is increasingly imported, coal expands[14] in Ecuador as a low-cost source for electricity generation and deforestation might compromise biodiversity and ecosystem services in the future.

8. Future work

The ELENA model, as stated before, is the first attempt of an IAM for Ecuador. The model structure is dynamic, and more detail and new technologies can be added to it. For instance, given the scarce direct normal irradiance (DNI) resources in continental Ecuador, solar thermal options were disregarded in the current version of ELENA. However, low-quality solar thermal applications could have been considered due to its significant potential [98], according to a recent release of Ecuador solar map 2019 [99]. Galápagos region has the highest DNI of the country, and a techno-economic potential of concentrated solar power technologies must be studied. Any renewable energy project carried in the archipelago is always emblematic due to its environmental importance. The same holds for other energy conversion technologies that were disregarded in this version of Elena: hydrogen-fuelled cars, trucks and ships, nuclear plants, and bio-digesters.

Another vital challenge refers to a better economic analysis required to complete the assessment of decarbonisation pathways in Ecuador. This significant drawback could be overcome in a second stage of the DDP project, where an economic model could be linked to ELENA. The economic analysis is fundamental, especially for developing countries. Socio-economic parameters are key to attain the decarbonisation pathways.

Given the relevance of BECCS in DDP scenarios, especially those with less reforestation, it is crucial to evaluate co-benefits and impacts of BECCS and reforestation, to propose the best decarbonisation strategy for Ecuador. A multi-criteria assessment could be a suitable methodology for that. It is necessary to understand the viability of CCS for Ecuador, and storage availability is fundamental. Studies have to be conducted to understand the storage capacity on depleted oil wells and in saline aquifers.

In order to properly assess emission and energy reductions related to efficiency, it is necessary to have detailed information of final energy uses. In Ecuador, some studies on this topic are available [100]. It is highly recommended to develop further studies to increase the data of final energy uses and increase the detail present in the model.

Finally, this study does not quantify co-benefits associated with public health, (e.g. lower local impact atmospheric emissions), jobs and income creation, local industry development, biodiversity, eco-tourism, etc. This is an important subject in emerging countries where other sustainable development goals must be aligned with DDP strategies.

Credit author statement

Daniel Villamar, Data curation, Formal analysis, Investigation, Writing – original draft. Rafael Soria, Conceptualization, Data curation, Writing – original draft, Writing – review & editing, Supervision. Pedro Rochedo, Conceptualization, Formal analysis, Methodology, Writing – review & editing, Software. Alexandre Szklo, Conceptualization, Formal analysis, Supervision, Methodology, Writing – review & editing. Mariana Imperio, Formal analysis, Writing – review & editing. Pablo Carvajal: Formal analysis, Writing – review & editing. Roberto Schaeffer, Conceptualization, Formal analysis, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

We thank the Deep Decarbonisation Pathways in Latin America and the Caribbean (DDP-LAC) project, financed by the Inter-American Development Bank (IADB) Sustainable Energy and Climate Change Initiative fund (RG-T3028), the IADB French Climate Fund (RG-T3193), the 2050 Pathways Platform, and the *Agence Française de Développement* (AFD). We thank *Institut du Développement Durable Et des Relations I*nternationales (IDDRI) by their technical support and coordination during the DDP project. We thank to Alejandra Guevara, Eduardo Noboa and Freddy Ordóñez for their support during initial stages of this work. We also value the information and feedback to our work provided by Verónica Guayanlema and Paúl Melo. We thank the Ministry of Environment (MAE), Ministry of Energy and Non-Renewable Natural Resources (MERNNR), Operator of the Ecuadorian Power System (CENACE) and Electric Corporation of Ecuador (CELEC) for sharing technical data. We thank to the *Escuela Politécnica Nacional* (EPN) for the research time to work on project PIE-DIM-BID-2019. Finally, we thank to the public company EPN-TECH for their administrative support. In the case of the Brazilian researchers, they also thank the Brazilian agency CNPq for the financial support.

[13] DDP scenarios indicate that approximately 25% of final energy consumption in the transport sector would be supplied by biorefinery diesel, while around 4% would be supplied by traditional biodiesel.

[14] Coal expansion is not a minor challenge for Ecuador, since it has never been part of the country's energy system. Nevertheless, it is a mature and cheap technology that could be considered in a poor planed transition from petroleum. The country does not have this resource nationally, but currently there is no legislation avoiding it to be imported or applied in the power sector.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2021.100637.

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