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Analysis of energy future pathways for Ecuador facing the prospects of oil availability using a system dynamics model. Is degrowth inevitable?

Vicente Sebastian Espinoza [a,d,*,1], Javier Fontalvo [a], Jaime Martí-Herrero [b,c], Luis Javier Miguel [d], Margarita Mediavilla [d]

[a] Instituto de Investigacion Geologico y Energetico (IIGE), Ecuador
[b] Biomass to Resources Group, Universidad Regional Amazonica Ikiam, Via Tena-Muyuna, Km.7, Tena, Napo, Ecuador
[c] Building Energy and Environment Group, Centre Internacional de Mètodes Numérics en Enginyeria (CIMNE), Terrassa, 08034, Barcelona, Spain
[d] Research Group on Energy, Economy and System Dynamics, Escuela de Ingenierías Industriales, Paseo Del Cauce S/n, University of Valladolid, 47011, Valladolid, Spain

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ABSTRACT

The aim of this paper is to develop a system dynamics model to assess the energy future up to 2050 for Ecuador considering its condition of oil producing country. Three scenarios have been developed with different assumptions regarding national and global oil availability under a Business-As-Usual narrative.

Energy demand would have a 2.4-fold increase by 2050 with predominance of petroleum products in a BAU scenario with unlimited oil access. In constrained scenarios, restricted availability of oil might pressure final demand to be reduced in 31%–40% compared to BAU. Limited imports of oil and petroleum products might produce shortages in supply, causing a downfall in economic activity in sectors with high dependency on these fuels Electricity would partially substitute fossil fuels but is not enough to offset economy decay in constrained scenarios. Limiting oil exports would not have an important effect since the decline of Ecuador's oil wells is expected to be too fast. Oil exports would cease by 2030–2045. When BAU scenarios are evaluated considering limited fossil energy access in a decaying world oil production, arise the necessity to explore new strategies to deal with an energy/economic shock.

1. Introduction

Energy is a key factor for human progress and economic development, driving the increase of living standards for the past decades. It is expected that global energy demand would rise due to population growth and improved social welfare. Future energy use requires the transition towards sustainable practices that include the development of widespread clean energy, and energy efficiency measures. An informed approach based on technical, economic, and environmental information is vital for this purpose [1].

The unifying structure that assists energy policymaking is provided by energy modelling. Energy models use data, a consistent theoretical framework, and modelling software to hand over quantitative information into alternative scenarios under assumptions with reasonable uncertainty. Constraints in energy modelling include policy targets such as equitable distribution, resource availability, technological transitions, and changes in the market structure [2]. Energy policy tools deriving from the application of energy modelling encompass international reviews, policy assessment processes, energy balances and long-term investment plans [3,4].

Integrated assessment models (IAMs) have been widely used to integrate social, economic, and ecological ramifications of a set of different natural and human factors, and their interactions. IAMs are computer models that seek to describe the potential evolution of a determined energy system through the association of constituent model blocks built based on mathematical representations from various fields. IAMs present a large variation between them in aspects such as the technological detail of the model, the detail level of the data, and the

Abbreviations: IAM, Integrated Assessment Model; EEDEC, Ecuadorian Energy Development under Energy Constraints; MBbl, Million Barrels; URR, Ultimately Recoverable Resources; ME, Maximum Exports; OS, Oil Sovereignty; SP, Stated Policies; SD, Sustainable Development; DR, Delayed Recovery.

* Corresponding author. Instituto de Investigacion Geologico y Energetico (IIGE), Ecuador.
E-mail addresses: sebastian.espinoza@geoenergia.gob.ec, vicente.espinoza@alumnos.uva.es (V.S. Espinoza).
[1] Avenida de la República E7-263 y Diego de Almagro, Edificio Sky, Quito, Ecuador, 170,518.

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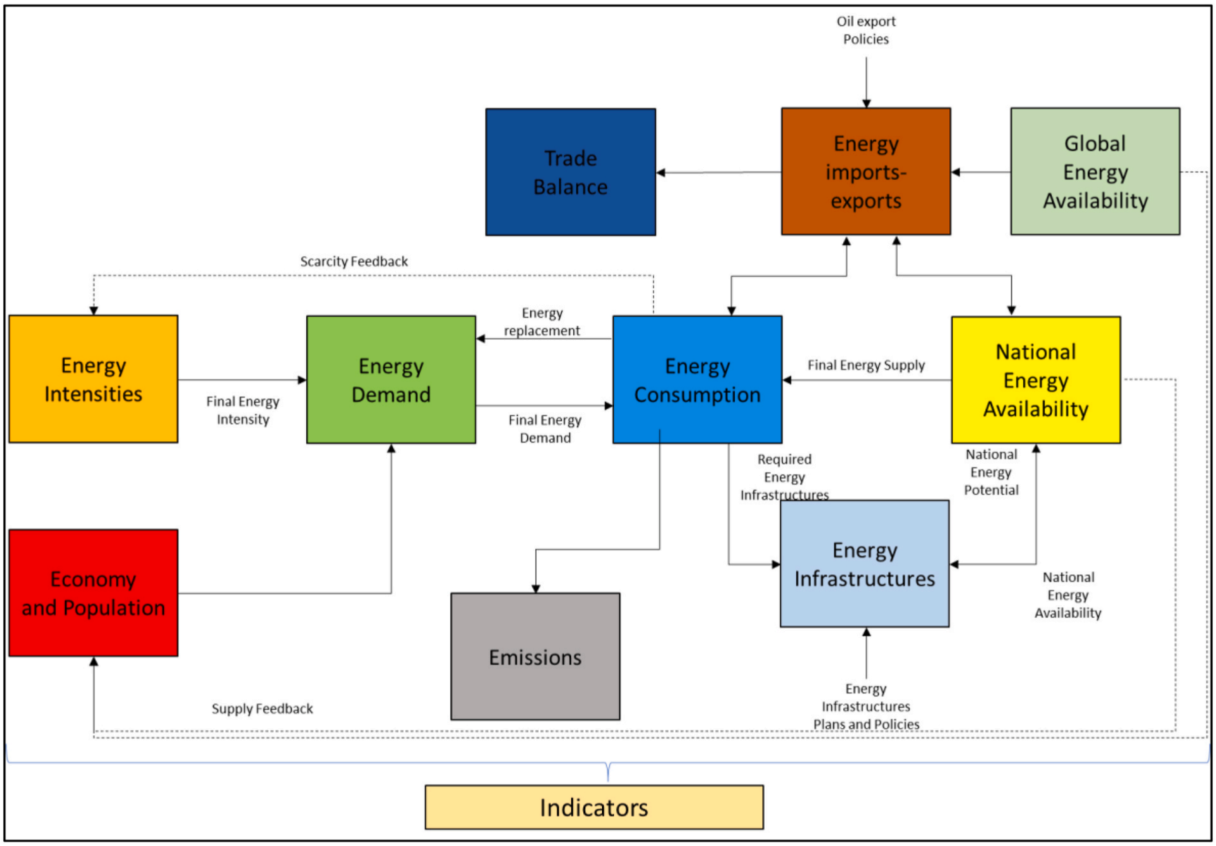


Fig. 1. Schematic overview of EEDEC model. The main variables connecting the different modules are represented by arrows.

presumed policy tools [5]. This variety can be noted in the large number of approaches tried to model the uncertainties of the complex interactions between models, remarkably in the case of environmental and climate change studies [6–11].

Most of the IAMs implemented in environmental and energy analysis present limitations posed by interactions and feedback within the models that do not fully apprehend the complexity of real systems [12,13]. Moreover, the use of simplified conventional economic optimization methods is not fully suitable to represent socioeconomic dynamics [14,15]. IAMs have been evolving to address some of these criticisms by incorporating more detailed representations of diverse modelling aspects, and additional analytical approaches [5,16–19].

Exploring alternative sustainable energy pathways through energy modelling has gained attention in the past years [20–23]. Instances of application of integrated assessment frameworks include the analysis at regional stages [24,25] or at specific energy demand sectors, like transportation [26]. The integrated assessment framework MEDEAS, introduced in Refs. [16,27], makes use of System Dynamics to expedite the integration of the different assumptions and fields, as well as the interactions between the various subsystems in the structure. MEDEAS model includes a novel approach that sets bio physical, economic, social, and technological restrictions that limit future energy supply and demand [16].

MEDEAS has considered to this point a global, regional, and country scale (with a focus on Europe). However, it is of interest to use some of its foundations to assess the dynamics of energy supply and energy demand in small oil producing countries, and small economies that are very vulnerable towards a necessary energy transition.

In Ecuador crude oil represents 88% of the primary energy produced [28], and 32% of the total exports in monetary terms [29]. It has been estimated that oil extraction peaked in 2014 with 203 million barrels and it would fall below 100 million barrels between 2023 and 2027 [30]. Other relevant aspects are the availability of renewable energy resources, fuel import requirements, the existing dynamics between petroleum products and final energy demand [31–33].

Previous studies have sought to model the impacts of different natural and social agents over the Ecuadorian energy system. Models have been developed to assess potential paths towards sustainable road transport [34,35], as well as a sustainable power generation system [36,37]. Furthermore, the same approach has been applied to forecast the potential impact of energy efficiency policies on energy demand, and decarbonization [38–42]. Few studies have explored system dynamics to model parts, or the complete Ecuadorian energy system [43–47]. However, given the particularity of Ecuador as an oil exporter, and as an importer of oil products, deeper attention must be taken to the dynamics of petroleum products demand, production, and imports, as well as oil extraction and exports. Moreover, it is on interest to analyze when and how potential future energy scarcity due to local and global physical constraints might affect energy demand and economic activity.

This paper is dedicated to evaluating energy scenarios under a Business-As-Usual narrative considering biophysical resource availability at national and global level for a small oil producing country, in this case Ecuador. For this aim, a new model based on system dynamics and novel modelling frameworks have been used. The potentialities of the model are shown through the analysis of the dynamics of energy supply and demand under a Business-As-Usual scenarios considering a case of no constraints, and local and global restrictions. Country's energy future, and possible decay in economic activity due to energy scarcity are evaluated under cases of oil availability, oil exports policies, and oil and petroleum products prices.

The paper is organized as follows: Section 2 presents the material and methods used for modelling; Section 3 introduces the proposed scenarios; Section 4 shows the results, Section 5 discusses the main findings, and Section 6 provides the conclusions.

Table 1
Energy sources modeled in EEDEC.

EEDEC energy source	NRE/RES	EEDEC primary and final sources of energy
Oil	NRE	Oil
Non-Associated Natural Gas	NRE	Non-Associated Natural Gas
Associated Natural Gas	NRE	Associated Natural Gas
Traditional Biomass (Wood)	RES	Traditional Biomass (Wood)
Ethanol	RES	Biomass
Modern Biomass (agricultural waste)	RES	Modern Biomass (agricultural waste)
Electricity	NRE	Oil Non-Associated Natural Gas Associated Natural Gas Gasoline LPG Diesel Oil Fuel Oil
	RES	Hydroelectricity Solar PV Onshore wind Geothermal power Biomass (agricultural waste) Biogas (livestock waste)
Oil Products (Gasoline, LPG, Kerosene-Jet Fuel, Diesel Oil, Fuel Oil, Gases, Non-Energy)	NRE	Oil Associated Natural Gas

Table 2
Technologies per transport type and segment included in EEDEC.

Transport type	Segment	Technology				
		Gasoline	Diesel	Hybrid	Electric	Natural Gas
Households	4 wheelers	✓	✓	✓	✓	
	2 wheelers	✓			✓	
Commercial	Light Duty	✓	✓	✓	✓	
	Heavy Duty	✓	✓	✓		✓
	Bus	✓	✓	✓	✓	✓
	VAN	✓	✓	✓	✓	

Table 3
Scenarios modeled in EEDEC based on BAU narrative.

Scenario Name	Description
BAU	This scenario considers unlimited imports of oil and petroleum products to satisfy the demand. It is used as reference to compare the effects of energy scarcity on supply and demand due global constraints
BAU_Const_2P	This scenario considers a national oil availability of 7800 MBbl (2P case from Ref. [30]) and import constraints of oil and petroleum products due to global oil availability. Oil export policy cases are applied.
BAU_Const_O	This scenario considers a national oil availability of 10,700 MBbl (O case from Ref. [30]) and import constraints of oil and petroleum products due to global oil availability. Oil export policy cases are applied.

Table 4
Description of the most relevant inputs and assumptions of each scenario developed under BAU narrative.

Inputs	Scenario Assumptions		
	BAU	BAU_Const_2P	BAU_Const_O
National Oil Availability [MBbl]	7800	7,800[a]	10,700[b]
Global Oil Availability	Unlimited	Ecuador would have access to the same share of global oil supply it has in global oil demand (0.2%). Global oil supply will follow Reference Scenario of [16].	Ecuador would have access to the same share of global oil supply it has in global oil demand (0.2%). Global oil supply will follow Reference Scenario of [16].
Sensitivity to scarcity	–	Medium (3) [27]	
Forgetting Factor	–	5 years [27]	
GDP yearly growth	Growth rates from Ref. [53] for the period (2020–2022) and 2.73% after 2022		
Energy intensity variation	Will follow inertial trends considering its evolution from 2000 to 2017.		
Vehicle technology share in Transport households	Will follow inertial trends considering its evolution from 2000 to 2017.		
Vehicle technology share in Transport commercial	Will follow inertial trends considering its evolution from 2000 to 2017.		
Electricity losses	Will decrease to 8.9% in 2027 [49]. From 2028 onwards it will remain constant.		
Installed Capacity RES	Electricity Master Plan base case until 2027 [49]. From 2028 onwards, capacity will increase at an annual average growth rate until 2050		
Annual average growth rate RES			
Hydro	7.8%		
Onshore wind	24.1%		
Solar PV	53.6%		
Geothermal	0.0%		
Biomass	6.1%		
Biogas	11.3%		
RES Potential			
Hydro	22,000 Mwe [49]		
Onshore wind	884 Mwe [49]		
Solar PV	16,637 MWp [83]		
Geothermal	2700 MWth [49]		
Biomass	92,233 TJ/Year [84]		
Biogas	223.4 TJ/Year [84]		
Electricity from Fossil Fuels	Will meet demand not satisfied by renewables plus 10% of total demand as reserve margin		
Fossil Fuels for Electricity	Current share to be maintained up to 2027 [28]: Oil: 19.4%, Natural Gas: 15.5%, LPG: 0.9%, Diesel Oil: 19.8%, Fuel Oil: 32.1%, Associated Natural Gas: 12.2%. From 2028 onwards, shares will change reaching in 2050 the following values: Oil: 0%, Natural Gas: 40%, LPG: 0%, Diesel Oil: 10%, Fuel Oil: 50%, Associated Natural Gas: 0%.		
Refining capacity	Constant with current values (60.7 MBbl/year) [28]		
Refining yield	Constant with current values [28] LPG: 2.2%, Gasoline: 18.6%, Kerosene/Jet Fuel: 5.2%, Diesel Oil: 24.3%, Fuel Oil: 46.7%, Non-Energy: 2.9%		
Natural Gas National Availability	655,414 Million cubic feet [80]		

[a] This value corresponds to the sum of proved and probable reserves used in [30].
[b] This value corresponds to the sum of proved, probable, and possible reserves plus contingent and prospective resources used in [30].

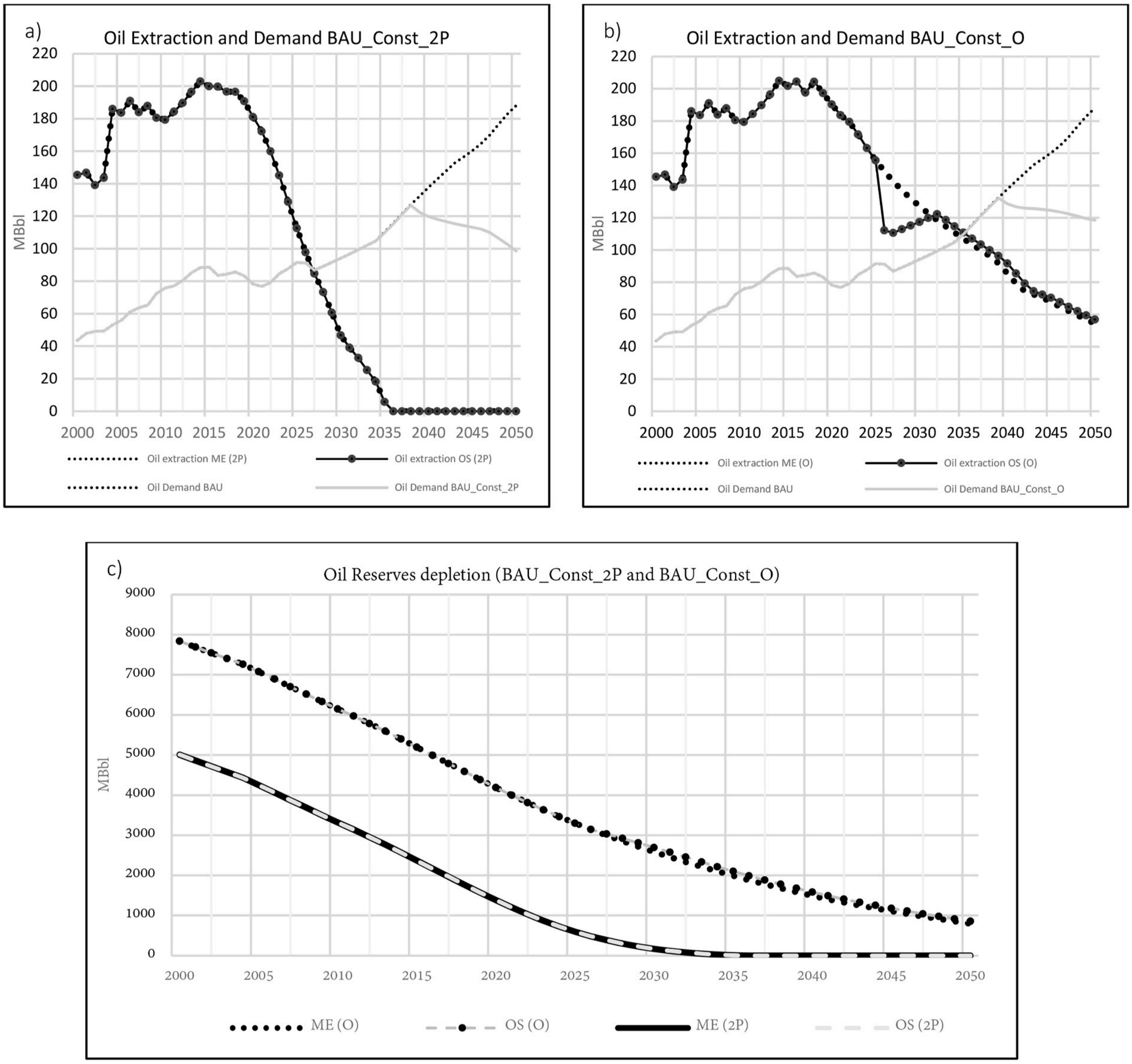


Fig. 2. Comparison of Oil extraction for each export policy and national oil demand for a) BAU_Const_2P and b) BAU_Const_O. c) Oil reserves depletion for each export policy for BAU_Const_2P, and BAU_Const_O scenarios.

2. Materials and methods

2.1. Ecuador energy context

Ecuador has been an oil producer, and net oil exporter since 1972 [30,48]. Historically, oil exports have accounted for around 75% of oil extracted [28]. Oil has a contribution of 10% to total Gross Domestic Product (GDP), and represents 18% of government revenues [28]. One of the main characteristics of Ecuadorian energy system is its small oil refining capacity (61.6 MBbl/year), and its yield with a large participation of fuel oil (47%), followed by diesel (24%), gasoline (19%), jet fuel (5%), non-energy, (3%) and liquified petroleum gas (LPG) (2%). Only 4% of the national demand of petroleum products is fuel oil and most of it is exported. The insufficient refining capacity has increased imports share to cover domestic demand.

In 2017 the share of imports in total supply for diesel, gasoline, and LPG were 56%, 55% and 76%, respectively [28]. These are the most demanded fuels, reaching a combined share of 71% in 2017 with respect to total demand. Gasoline and diesel are mostly used in transport, the most energy intensive sector with 49% of total energy demand.

Regarding electricity, during the last decade national plans have fostered power capacity expansion based on the country's large hydropower potential (22,000 MW) [49]. As of 2018, total installed capacity reached 8662 MW, and hydropower capacity 5067 MW. The expansion in power capacity made Ecuador a net electricity exporter in 2018 [50].

2.2. Overview of modelling framework

Ecuadorian Energy Development under Energy Constraints (EEDEC) is a simulation model based on system dynamics that eases the integration of different perspectives and feedbacks from all the components of the system and its variables; the schematic overview of the model is depicted in Fig. 1. It has been used to reference some of its subsystems the dynamic recursive models MEDEAS and WoLiM [16,51].

The model was developed in Vensim DSS software for Windows Version 8.1.1 Double precision (x64), runs from 2000 to 2050, and manages 14 energy sources (Table 1). It has been structured into six modules: energy demand, energy availability, energy infrastructure, emissions, and energy indicators.

EEDEC works along these lines: for each period, final Energy demand is computed based on GDP and energy intensities for each sector and source. Energy supply to cover projected demand will depend on

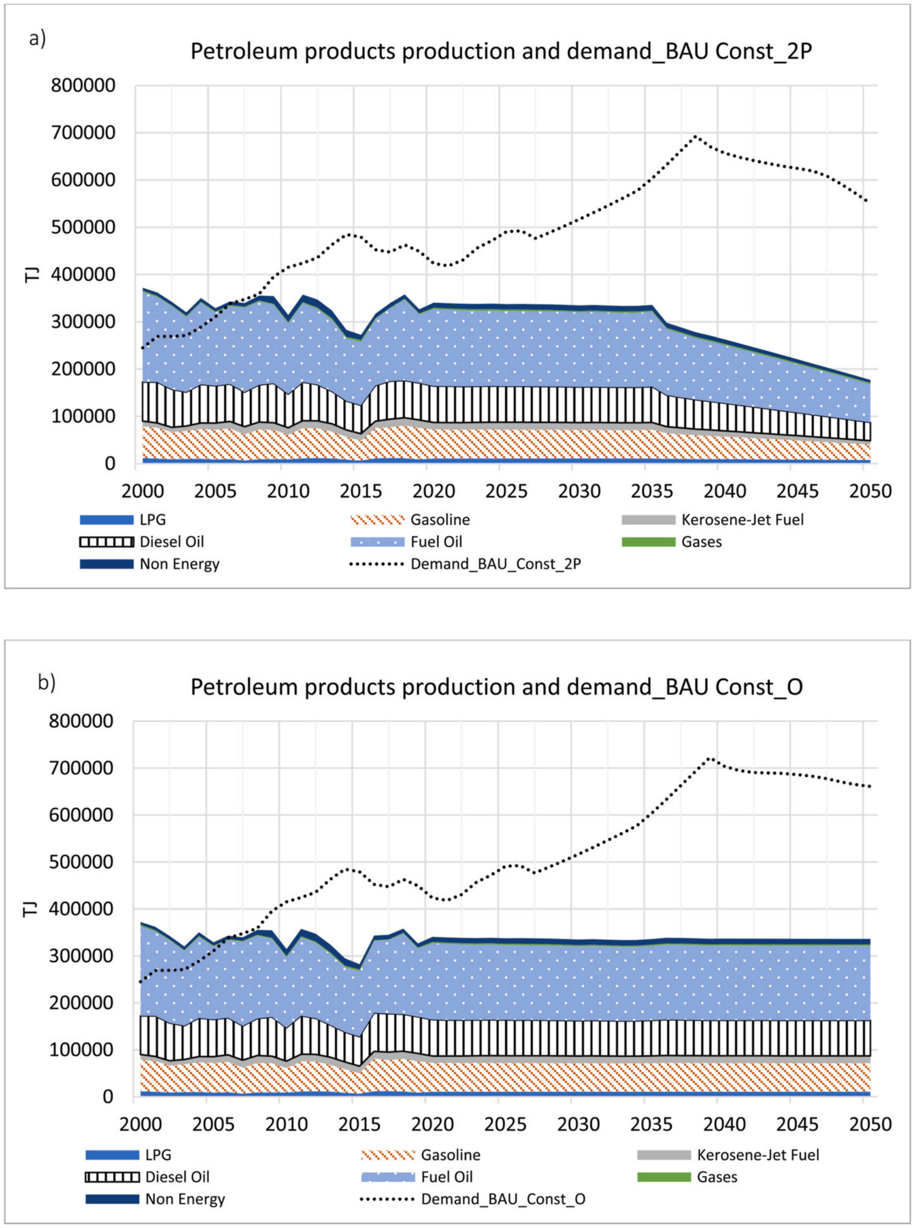


Fig. 3. Petroleum Products Production and demand for each scenario a) BAU_Const_2P, b) BAU_Const_O.

national and global energy availability, and energy infrastructures. If energy supply is shorter than demand, the system on one side will foster energy intensity improvements and on the other will try to replace current sources with less scarce ones based on established limits. Once the limits regarding energy intensity improvement and source substitution have been reached, the system will adjust economic activity based on energy availability. GHG emission will be computed as well as fossil fuels trade balance, energy imports and exports, and indicators. Supplementary material offers a detailed description of the model.

2.3. Description of EEDEC model

2.3.1. Economy

The evolution of socio-economic drivers (GDP, population, households demand) are exogenously defined based on the economic model proposed by Ref. [40]. GDP and demand from households was updated based on the current data from Ref. [52], and projected GDP annual growth rate was adjusted based on new short term perspectives for Latin American [53]. GDP was aggregated in four sectors: Industry, Commercial and Public, Transport, and Other Sectors, plus for households' demand. Even though GDP is exogenously defined, it will be adjusted based on energy availability as it will be described in the next section.

2.3.2. Energy demand

Energy demand depends on technological development, energy availability, and policies implemented [54,55]. For estimating future energy demand, two approaches have been used [56]: (1) a top down approach that uses projections of aggregated sectoral trends through GDP, and energy intensities; and (2) bottom-up approach that considers subsectors, and technologies used in each subsector.

Energy demand (FED_{ik}) per sector and final source is the product of GDP per sector X_i and sectoral energy intensities for each final energy source EI_k (Eq. (1)). Even though this indicator has both an engineering and macroeconomic concept [57], the latter has been used for estimating future energy demand in several models [39,45,58–61].

$$FED_{ik} = EI_{ik} * X_i \tag{1}$$

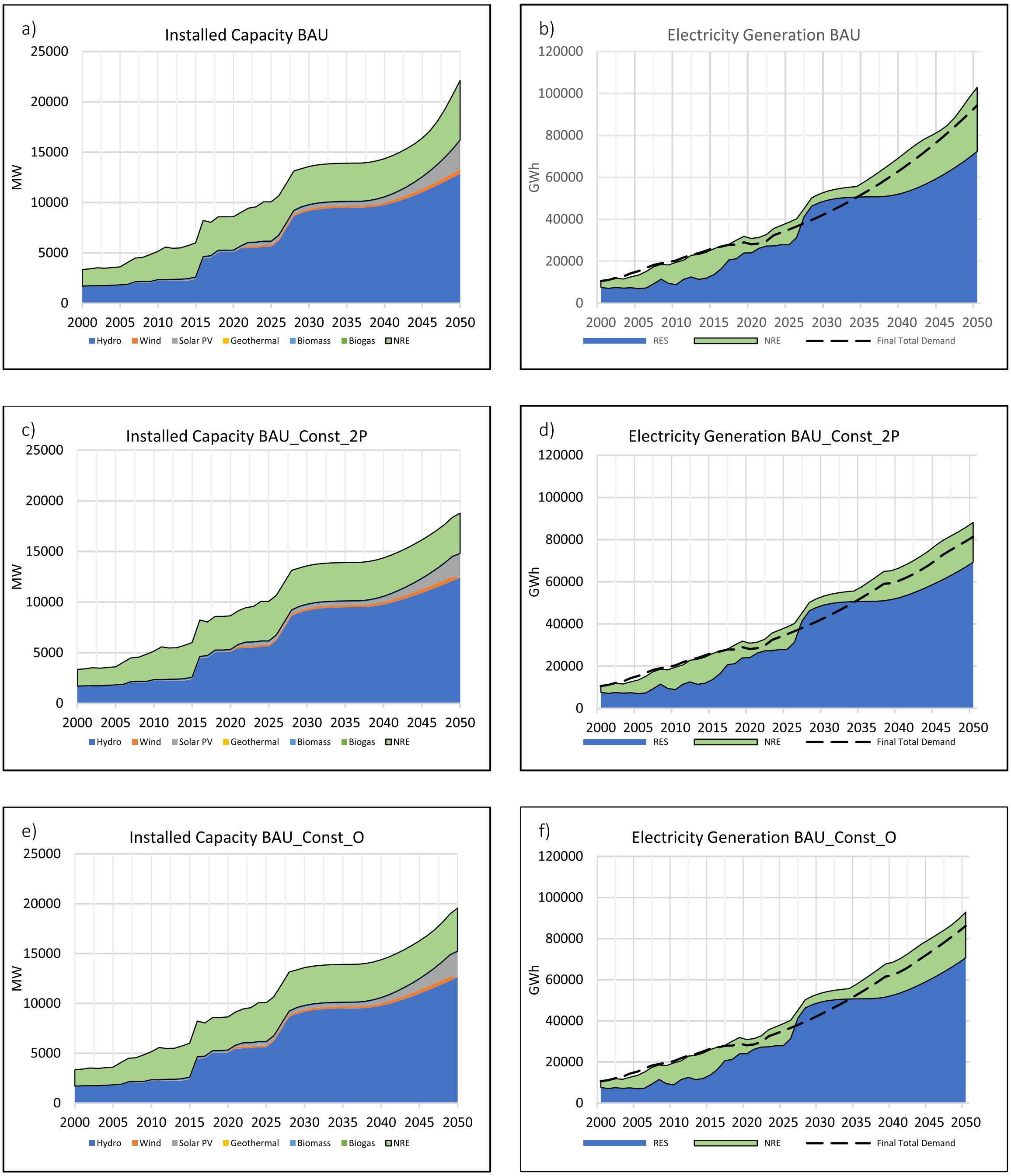


Fig. 4. Total installed capacity, electricity generation by RES and NRE and electricity demand for each scenario a)-b) BAU, c)-d) BAU_Const_2P, e)-f) BAU_Const_O.

All sectors are modeled using a top-down approach except for Transport that has been modeled using both top-down and bottom-up methodologies.

To model the dynamics of energy intensity, available data from National Energy Balances (2000–2017) and Central Bank of Ecuador (2000–2017) was used as reference to calculate historical energy intensities and the average of relative annual variation ($\overline{\Delta EI_{ik}{}^{h}}$). This is the baseline trend and the first component that describes the evolution of energy intensity. This trend may change in the future based on two factors: (1) Variation attributed to the implementation of energy efficiency measures for the current technology and sources used in each sector ($\Delta EI_{ik}{}^{eff}$), and (2) Variation attributed to source substitution ($\Delta EI_{ik}{}^{sub}$). The total variation of energy intensity per sector and source is shown in Eq. (2).

$$\Delta EI_{ik} = \overline{\Delta EI_{ik}{}^{h}} + \Delta EI_{ik}{}^{eff} + \Delta EI_{ik}{}^{sub} \quad (2)$$

Two main aspects will drive the variation of energy intensity: the first involves market factors associated to the scarcity of each source k (perception of scarcity PS_k), due to the dynamics of natural resources extraction, its physical availability, and import-export policies. This is an alternative perspective that considers physical scarcity of energy sources instead of energy price to reflect imbalances between energy supply (FES_k) and demand (FED_k). The second aspect gathers policies that foster energy efficiency of current sources used as well as source substitution.

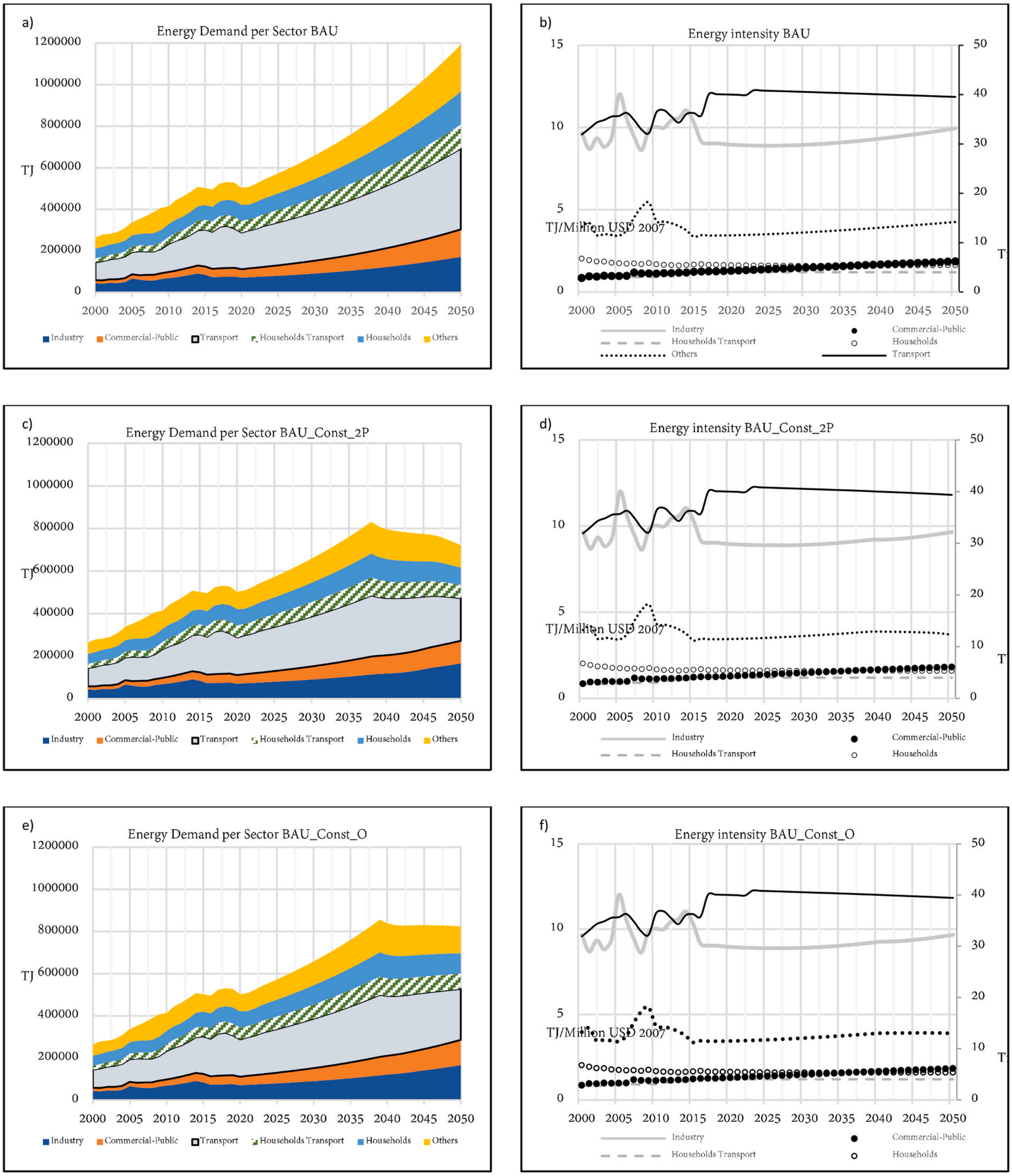


Fig. 5. Energy demand and energy intensity per economic sector for each scenario a)-b) BAU c)-d) BAU_Const_2P, e)-f) BAU_Const_O.

$$\Delta EI_{ik}{}^{eff} = \left(PS_k + Policy\ Effects^{eff}\right)*Max_{ik}^{eff} \tag{3}$$

$$\Delta EI_{ik}{}^{sub} = \left(PS_k + Policy\ Effects^{sub}\right)*Max_{ik}^{sub} \tag{4}$$

Maximum variations of intensity due to efficiency and fuel substitution have been obtained based on historical data and statistical analysis. (See Supplementary Material).

The variable perception of scarcity (Eq. (6)) as used in Ref. [27] cumulatively increases its value when demand exceeds supply and decreases if no shortages are registered. It depends as well on the actual scarcity of energy source k (Eq. (5)), the sensitivity to scarcity (SS) that sectors may have, and the time that takes to disregard scarcity (Forgetting Factor FF).

$$Scarcity_k = \frac{FED_k - FES_k}{FED_k} \tag{5}$$

$$PS_k(t) = Scarcity_k * SS + \frac{PS_k(t-1)}{FF} \tag{6}$$

Effects of scarcity in the economy have been included in EEDEC model considering energy supply. After the system has reached its maximum limits of reducing energy intensity and substituting energy sources, economic activity might be adjusted based on energy supply according to Eq. (7).

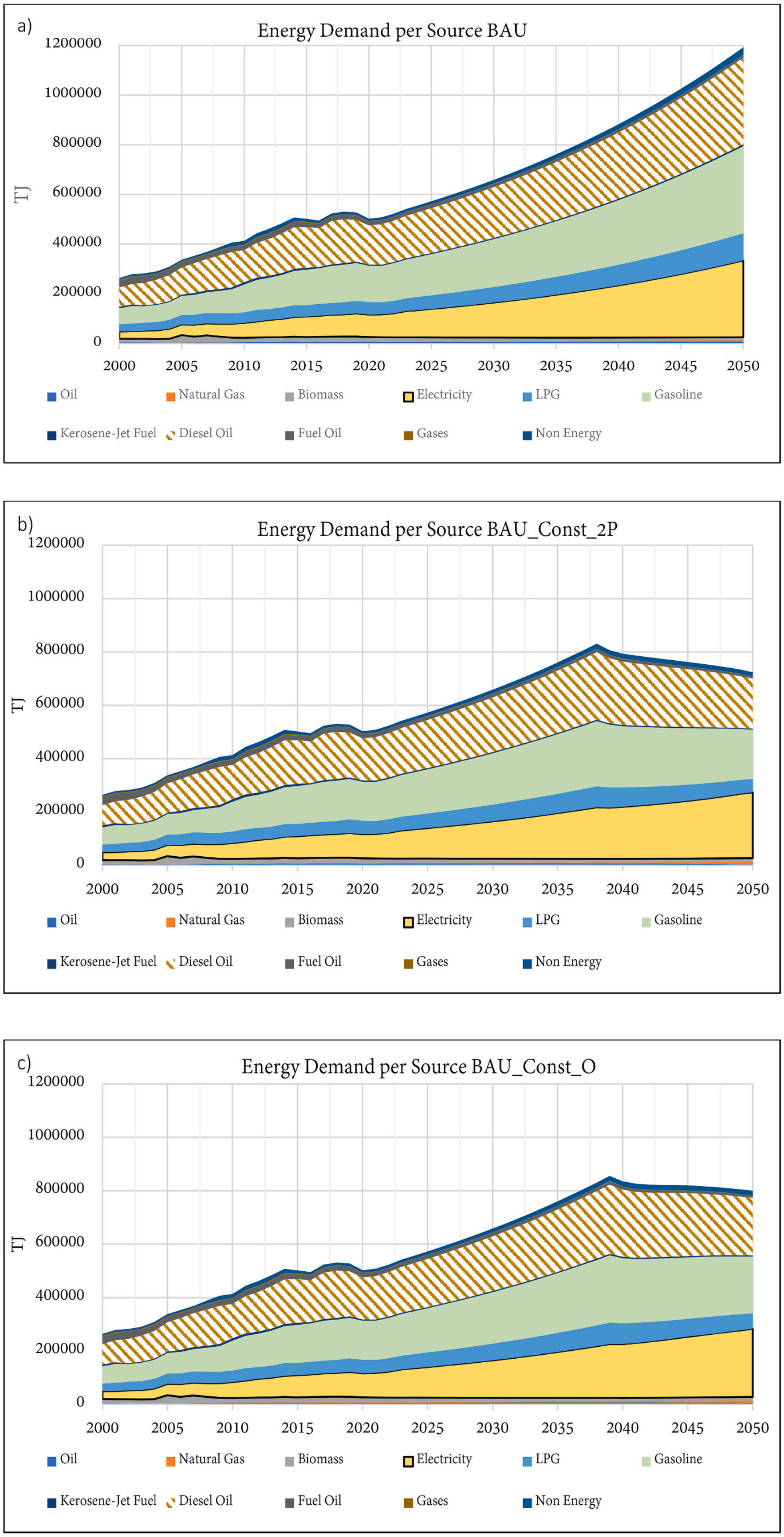


Fig. 6. Energy demand per source for each scenario a) BAU b) BAU_Const_2P, c) BAU_Const_O.

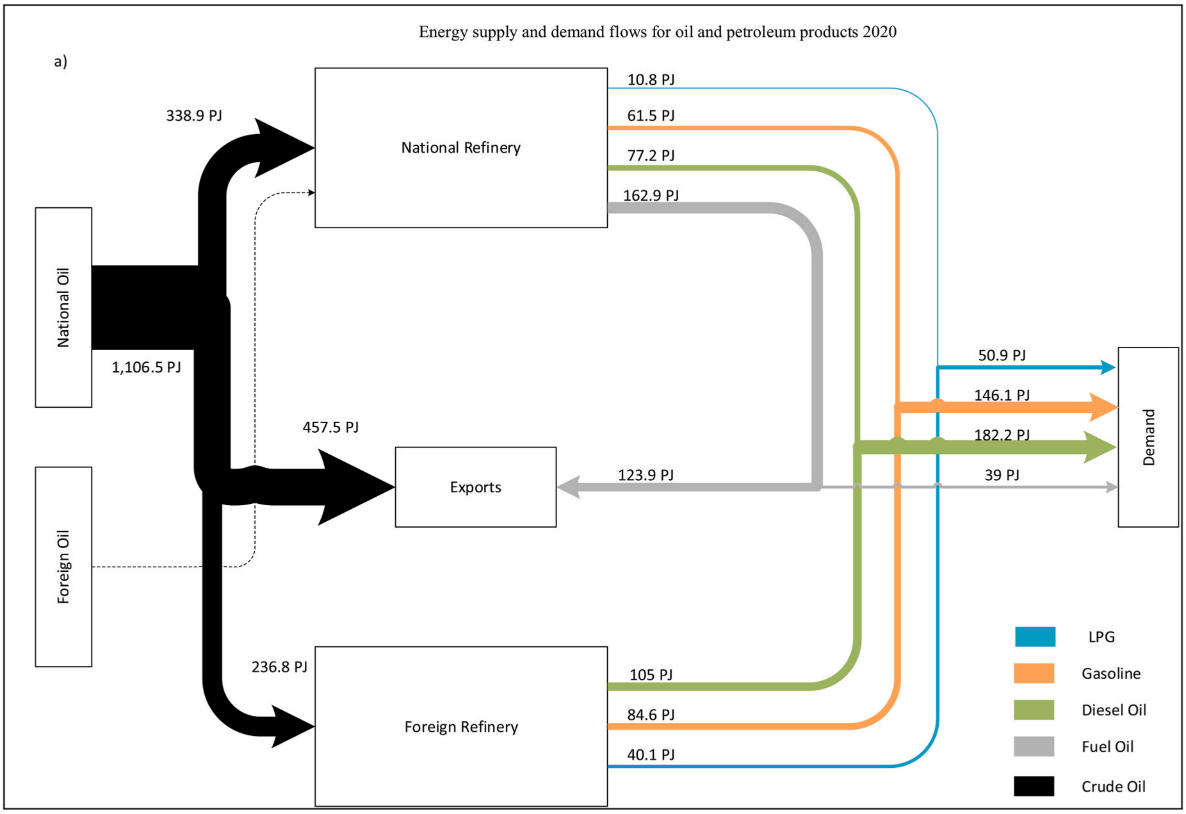


Fig. 7. Energy supply and demand flows for oil and petroleum products in 2020 a), and in 2050 under b) BAU_Const_2P and c) BAU_Const_O scenarios. Flows with dashed lines represent zero value.

$$\sum_{k=1}^{n} Supply_{ki} = X_{i_{adj}} * \sum_{k=1}^{n} (EI_{ki}) * (Share_{ki}) * (Share\ Total\ Demand_{ki}) * (Share\ Sector_{ki}) \qquad (7)$$

where:

Supply$_{ki}$: Is the supply of energy source *k*, for sector *i*.

$X_{i_{adj}}$: Is the adjusted economic activity for sector *i*.

EI$_{ki}$: Is the energy intensity of energy source *k*, for sector *i*.

Share Total Demand$_{ki}$: Is the share in total demand of energy source *k*, for sector *i*.

Share Sector$_{ki}$: Is the share of energy source *k* in the demand of sector *i*.

2.3.3. *Energy availability*

Availability of non-renewable energy (NRE) at national level has two constraints: the available source in ground or stock, and the extraction rate or flow. The latter can be constrained by infrastructure, technology, or policies, whereas the first is bounded by geological restrictions [62–65].

Future availability of oil and natural gas will depend on depletion curves that consider limits for stock and flow over time. The curves represent maximum extraction levels over time based on geological restrictions. The literature available for oil depletion curves in Ecuador is scarce with only few studies identified [30,66,67]. The model used in Ref. [30] has been chosen as reference for depletion curves, which are converted into maximum extraction curves as a function of remaining reserves. (See Supplementary Material). Fossil fuels imports are constrained by global oil supply taken from Ref. [16]. and the share that the country has had in total world demand.

2.3.4. *Energy infrastructures*

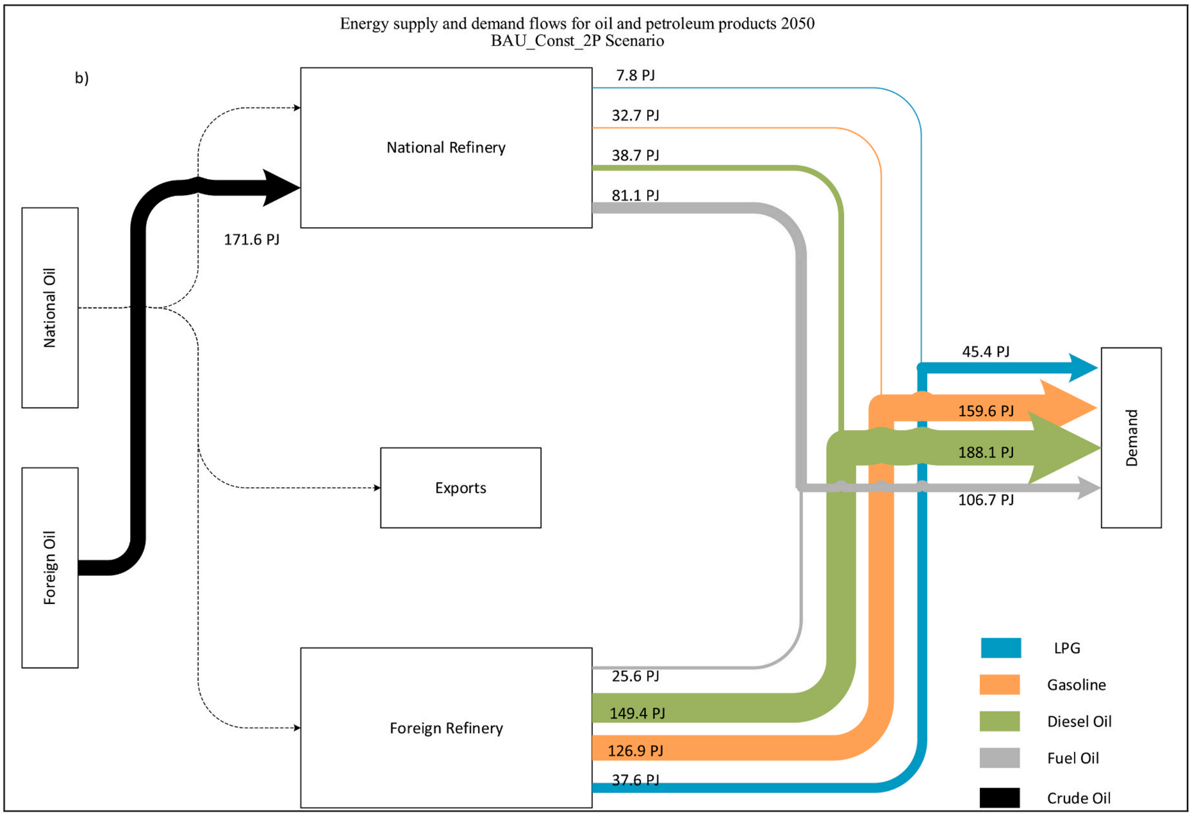
The infrastructures for electricity generation, oil products production and biofuels are represented in the model as stocks with a specific lifetime and increase according to the requirements, and policies. RES power capacity is limited by the resource potential, following a logistic growth, and its deployment depends on the intermittency of variable RES, which is based on overcapacities [68] depending on the penetration of RES in the mix. If power capacity addition is required to cover projected electricity demand, the model will prioritize RES in alignment with ongoing government plans until 2027. From this point forward, the model will consider inertial growth rates of renewables and electricity from NRE will be considered to satisfy demand if RES capacity is not sufficient, and as reserve margin (10% of demand).

2.3.5. *Transport*

Transport is segmented in Transport for Households (private vehicles) and Commercial Transport (that includes water and air transport). A detailed modelling has been proposed using a bottom-up perspective for both households and commercial road transport. Other types of transport (water and air) have been aggregated and modeled using a top-down approach.

Vehicle types and technologies for households, and commercial road transport are shown in Table 2. Depending on vehicle type, special attention has been given to technologies that are likely to have a significant share in vehicle fleet in the future. Alternatives such as heavy-duty electric vehicles, or hybrid two wheelers have not been included [69,70].

Regarding the number of vehicles, it has been considered that mobility patterns will remain the same [26], and it will be determined by economic demand. Thus, energy intensity will vary depending on technology share for each vehicle type. Eq. (3) describes energy intensity of gasoline in households' transport.



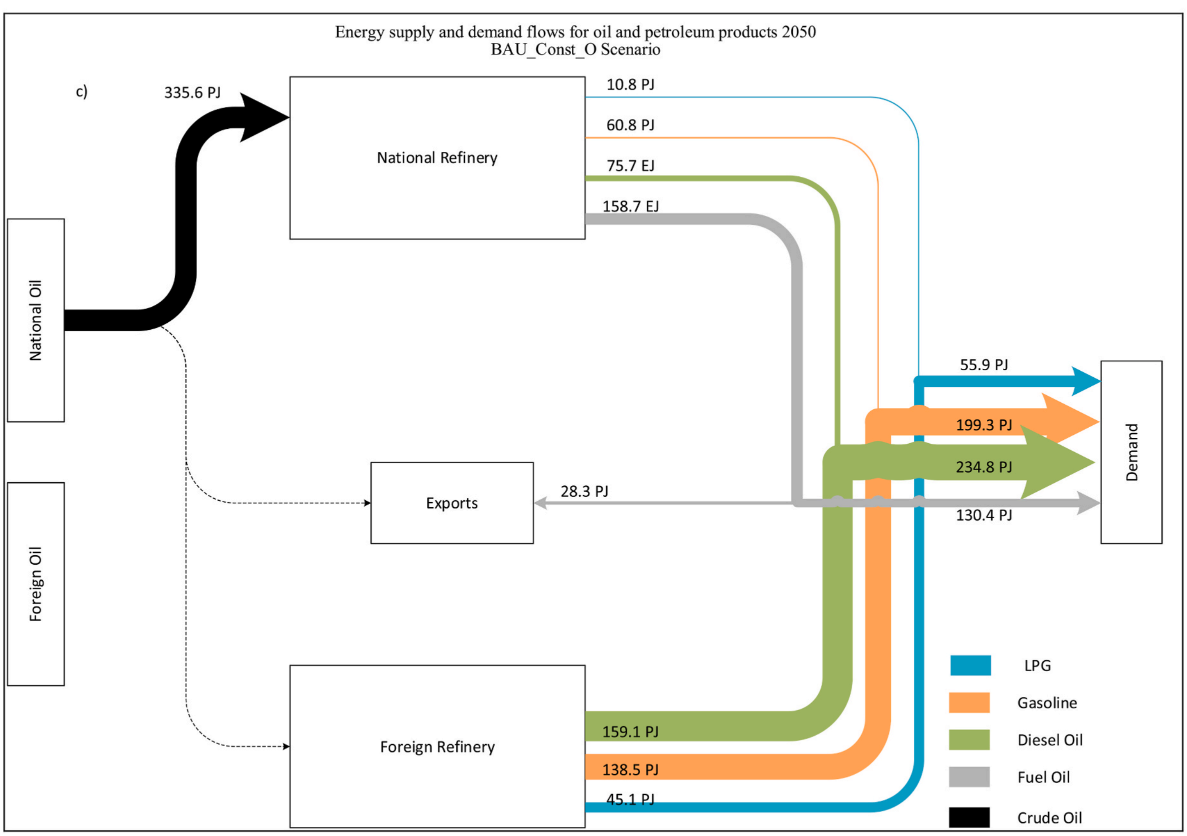


Fig. 7. (*continued*).

Table 5
Indicators for oil and petroleum products.

	Export Policy	2020	2025	2030	2035	2040	2045	2050
Gross Oil exports [MMBbl]								
BAU_Const_2P	ME	119.4	50.2	0.0	0.0	0.0	0.0	0.0
	OS	119.4	50.2	0.0	0.0	0.0	0.0	0.0
BAU_Const_O	ME	128.5	93.1	67.3	46.5	24.0	7.4	0.0
	OS	128.5	93.1	57.5	50.3	30.2	10.2	0.0
Net Oil exports [MMBbl]								
BAU_Const_2P	ME	80.5	1.4	0.0	0.0	0.0	0.0	0.0
	OS	80.5	1.4	0.0	0.0	0.0	0.0	0.0
BAU_Const_O	ME	89.7	44.4	9.8	0.0	0.0	0.0	0.0
	OS	89.7	44.4	0.0	0.0	0.0	0.0	0.0

$$EI\ HHT_{Gas_t} = \frac{HH{*}\%HH_{4wGas}{*}Av.Dist_{4W}{*}Eff_{4WGas}}{HHcons} + \frac{HH{*}\%HH_{4wHyb}{*}Av.Dist_{4W}{*}Eff_{4WHyb}}{HHcons} + \frac{HH{*}\%HH_{2wGas}{*}Av.Dist_{2W}{*}Eff_{2WGas}}{HHcons} \quad (8)$$

HH is the total number of household vehicles, $\%HH_{4wGas}$, $\%HH_{4wHyb}$, $\%HH_{2wGas}$ are the share of technologies for four and two wheelers; $Av.Dist_{4W}$ and $Av.Dist_{2W}$ the average distance in kilometers covered in a year by four wheelers and two wheelers; Eff_{4WGas}, Eff_{4WHyb}, Eff_{2WGas} are the vehicle efficiencies or energy used per kilometer.

The variation of energy intensity by final source is expressed as its derivative and can be represented as a function of energy demand and household's demand in monetary terms (*HHcons*), or transport GDP, and the changes in the share of vehicle technologies (Eq. (9)).

$$\frac{d}{dt}(EI\ HHT_{Gas}) = \frac{d}{dt}\left(\frac{HH{*}\%HH_{4WGas_t}{*}Av.Dist_{4W}{*}Eff_{4WGas}}{HHcons} + \frac{HH{*}\%HH_{4WHyb_t}{*}Av.Dist_{4W}{*}Eff_{4WHyb}}{HHcons} + \frac{HH{*}\%HH_{2WGas_t}{*}Av.Dist_{4W}{*}Eff_{2WGas}}{HHcons}\right) \quad (9)$$

If current mobility patterns would continue, number of vehicles, average distance covered, vehicle efficiencies, and household's demand can be assumed constant. Vehicle efficiencies are relative to the efficiency of gasoline vehicles using saving ratios (sr_{hyb}). Energy intensity variation can be expressed as Eq. (10):

$$\frac{d(IE_{Gas_t})}{dt} = A_1\frac{d(\%HH_{4wGas})}{dt} + A_1\frac{d(\%HH_{4wHyb}{*}sr_{hyb})}{dt} + A_2\frac{d(\%HH_{2wGas})}{dt} \quad (10)$$

where:

$$A_1 = \frac{HH{*}Av.Dist_{4W}{*}Eff_{4WGas}}{HHcons} \quad (11)$$

$$A_2 = \frac{HH{*}Av.Dist_{2W}{*}Eff_{2WGas}}{HHcons} \quad (12)$$

Saving ratios were taken from literature (0.66 - hybrid cars [71], 0.95 - hybrid heavy duty vehicles [72,73], 1 -natural gas vehicles [74, 75], 0.33 - electric vehicles [26], 0.5 - electric buses [26].

Introduction of new technologies are modeled based on the variation of their share in total vehicles that follow a logistic function described in Eq. (13), taking as example electric four wheelers.

$$\%HH_{4wElec}(t) = \frac{Max\%HH_{4wElec}}{1 + a{*}e^{-b{*}t}} \quad (13)$$

where, $\%HH_{4wElec}(t)$ is the share of electric 4wheelers in time *(t)*, $Max\%HH_{4wElec}$ is the maximum estimated share to be reached, *a* is the slope factor and *b* is the growth rate taken from literature [76]. The same approach was used for commercial road transport.

2.3.6. Emissions, indicators, and trade balance

Emissions related to resource extraction, final energy demand, and electricity generation are calculated. Three gases are considered: CO_2, CH_4 and N_2O using IPCC Guidelines and emission factors [77]. Energy transition indicators include:

- Final energy carbon intensity: emissions of GHG per unit of final energy
- Power Carbon intensity: emissions of GHG per unit of electricity generated.
- Electricity share in final demand: participation of electricity in total final energy demand.

Indicators for oil and petroleum products include:

- Gross Oil exports: quantifies the amount of crude oil exported, which depends on export policies and oil availability.
- Net Oil exports: difference between gross oil exports and oil imbedded in imported petroleum products. This indicator provides a real image of Ecuador's status as oil exporter.

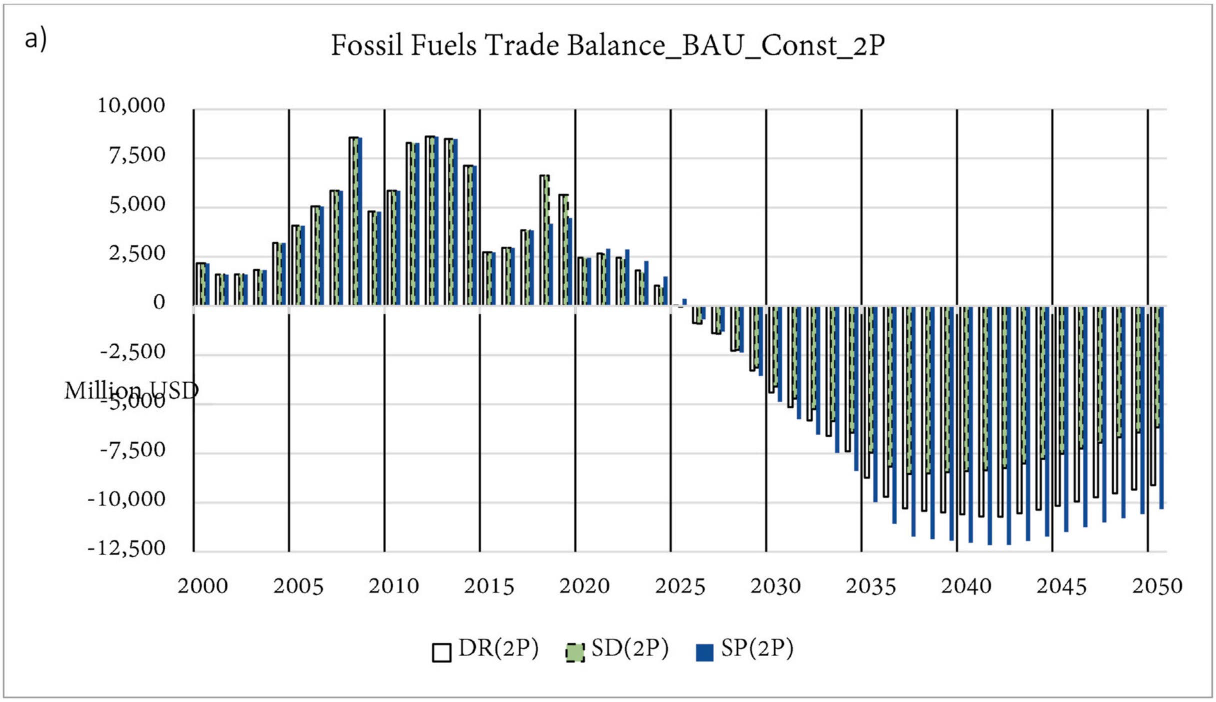
Fossil fuels trade balance is computed using oil and natural gas prices projections from IEA and the three scenarios developed in [78].

i. Stated policies (SP): considers existing policies, and measures implemented up mid 2020 that affect energy markets.
ii. Sustainable Development (SD): integrates policies aimed at achieving objectives included in the sustainable development goals 7, 3.9, and 13.
iii. Delayed Recovery (DR): depicts uncertainties in global economy related to the pandemic. Economic recovery is considered to take more time and to be weaker than in SP scenario.

Petroleum products prices were calculated based on IEA oil prices and the methodology used in Ref. [30]. (See Supplementary Material).

3. EEDEC simulation

The capabilities of EEDEC are depicted in the simulation of three



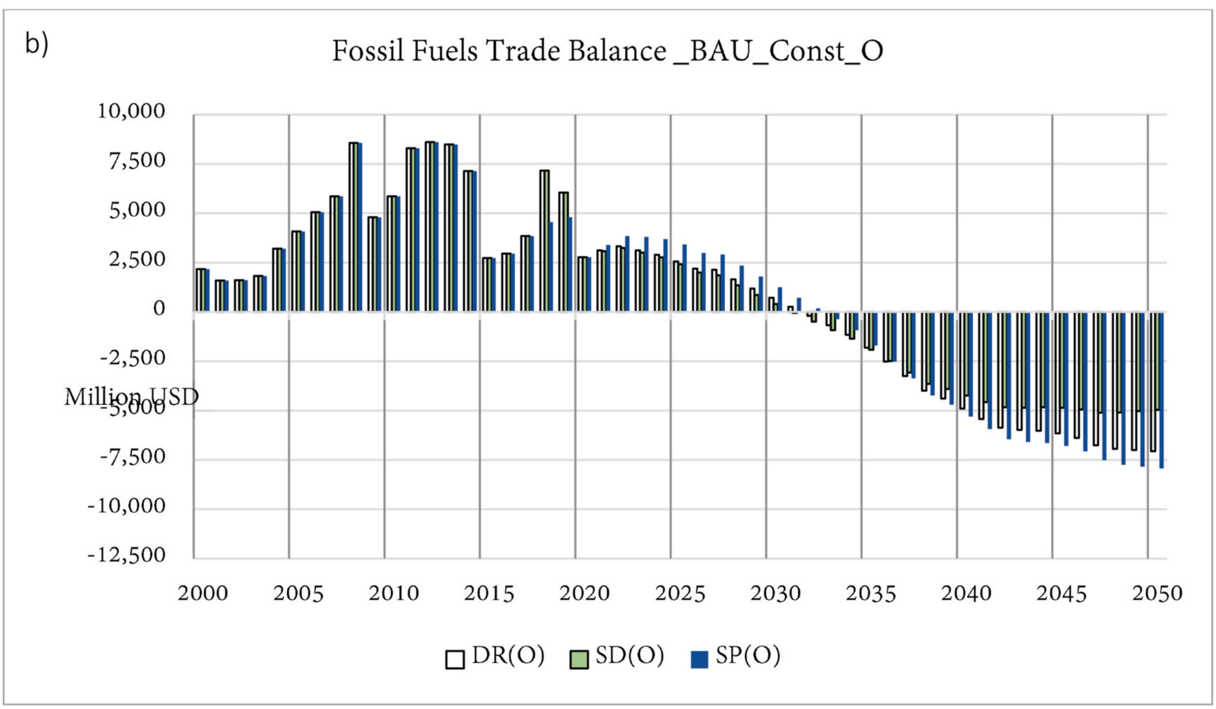


Fig. 8. Fossil fuels trade balance for ME export policy under oil prices scenarios a) BAU_Const_2P, and b) BAU_Const_O.

scenarios described in Table 3 under a Business-*as*-Usual (BAU) narrative in terms of economic growth, evolution of energy intensity, and development of energy infrastructures. Exploring alternative narratives and scenarios is the next step of the present work given that it requires a more complex analysis with a broader set of hypotheses for energy supply and demand.

3.1. Definition of scenarios and policy cases

BAU storyline is used in energy modelling as a baseline to compare the effects that policies, or restrictions for supply and demand might have in the future. In this research, a BAU scenario with unlimited access to oil is compared with two BAU scenarios with restrictions in terms of national and global oil availability Changes in energy demand are based on historical trends, whereas past trends and ongoing transformations define energy supply and infrastructures. The set of inputs for the BAU narrative in terms of energy supply and demand has been developed based on the analysis of national energy statistics [28,50,79,80], and current national plans [49,81]. The economic inputs for the model have considered the contraction due to the pandemic depicted in Ref. [53] for

Table 6
Evolution of Energy Transition Indicators for BAU_Const_2P and BAU_Const_O scenarios.

	2020	2025	2030	2035	2040	2045	2050
Emissions from Final Demand [Million Ton CO2Eq]							
BAU_Const_2P	29.42	32.42	36.46	41.25	41.81	37.94	31.73
BAU_Const_O	29.42	32.42	36.44	41.21	44.28	41.19	37.76
Final Energy Carbon Intensity [TonCO2Eq/TJ]							
BAU_Const_2P	58.51	56.61	55.35	54.23	52.46	49.01	43.99
BAU_Const_O	58.51	56.61	55.34	54.19	52.80	49.63	45.82
Power Carbon Intensity [TonCO2Eq/GWh]							
BAU_Const_2P	192.56	234.04	83.02	104.55	178.71	194.79	178.54
BAU_Const_O	192.56	234.04	83.00	105.92	197.01	206.38	197.97
Electricity Share in Final Demand [%]							
BAU_Const_2P	18%	20%	21%	23%	25%	28%	34%
BAU_Const_O	18%	20%	21%	23%	24%	27%	32%

2020, 2021, and 2022. After this, it is expected that the economy might tend to stabilize, and GDP growth rate would be 2.73% [37]. This scenario case structure allows us to depict the implications of oil physical availability, oil extraction (based on exports policies), and energy prices in Ecuador's energy system and trade balance if current trends in terms of demand and supply are maintained.

Regarding oil availability, maximum extraction curves as a function of oil remaining reserves were obtained for the two cases of ultimate recoverable resources (URR) (2P: 7800 MBbl, and O: 10,700 MBbl) taken from [30].

Given the dependence on oil as energy and income source and its progressive extraction decay and depletion of reserves, it is worth assessing policies for oil exports to avoid a rapid decline in reserves and revenues. Two cases for export policies are evaluated with the constraint of maximum extraction curves:

- Maximum Exports: the country will seek to export the maximum amount of oil. During the last decade oil revenues have represented on average 20% of total revenues, and oil exports 46% of total exports [52,82].
- Oil Sovereignty: this policy will seek to avoid abrupt depletion of oil reserves. For this purpose, it will export only the amount of oil embedded in imported petroleum products necessary to cover domestic demand.

Table 4 describes the most important inputs and assumptions that are part of the BAU narrative for the three scenarios proposed.

4. Results

This section presents the results of the simulation for the proposed scenarios. The evolution of energy supply will be analyzed first, then energy demand and energy intensity will be presented. Indicators, emissions, trade balance and estimated degrowth for constrained scenarios will be described.

4.1. Energy supply

4.1.1. Crude oil extraction and petroleum products production

Fig. 2 a) compares oil extraction profiles based on export policies and oil demand for BAU and BAU_Const_2P (sector's final demand of oil products converted to oil). Extraction declining rates would reach yearly values of 5% in 2021 and 69% in 2035. Fig. 2 a), and c) show the negligible effects of export policies, since the two cases have similar extraction profiles, and oil reserves will be depleted by 2036 (Fig. 2 c)). Due to the pressure to reduce the demand of scarce petroleum products and the reduction in economic activity specially in sectors with high dependency on these fuels, oil demand in BAU_Const_2P would be 48% lower than BAU by 2050. In 2026, oil extraction would reach 100 MBbl, (half its maximum historic value), and by 2027 extraction and oil demand would intersect. This means that Ecuador might become a net oil importer from 2027 forward in BAU_Const_2P scenario.

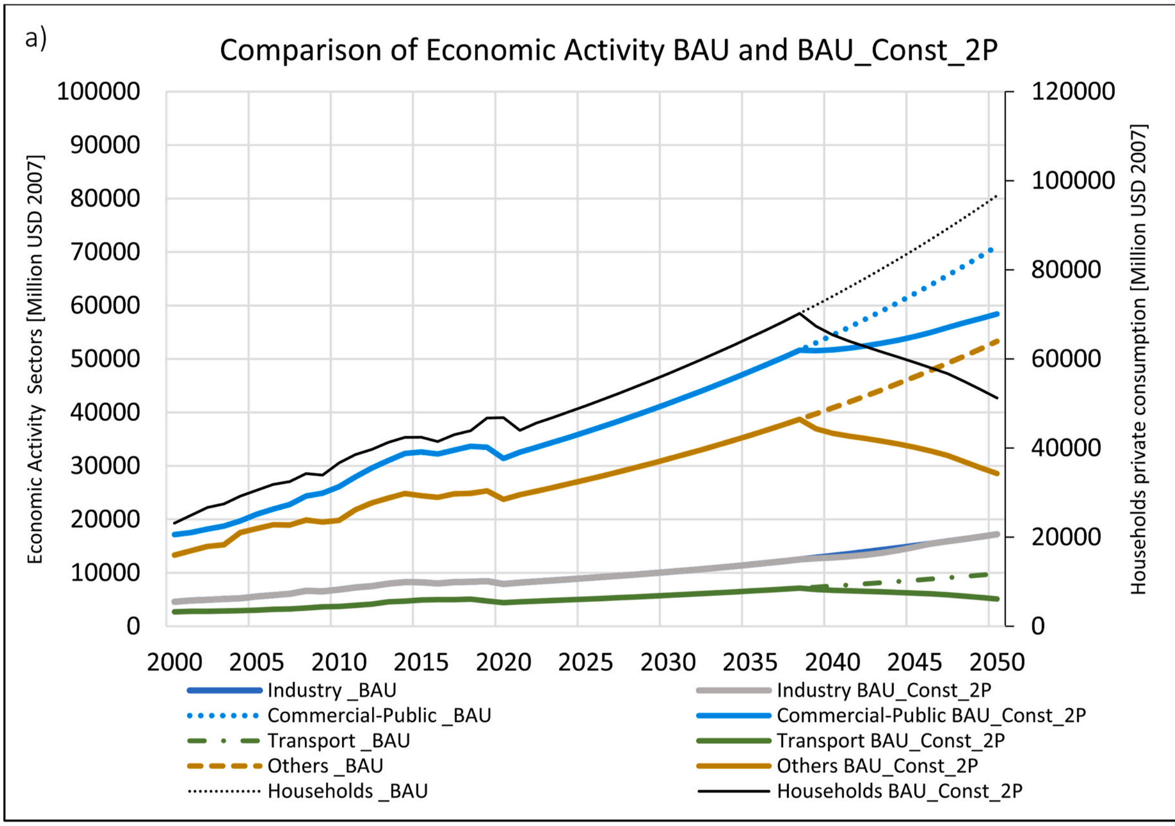
Under an optimistic scenario (Fig. 2 b)), oil demand and extraction would intersec by 2035, and half historic maximum extraction would be reached by 2037. OS policy would have a noticeable effect on oil extraction from 2026 to 2030 with reductions from 36 to 10 MBbl with respecto to ME policy. After this, due to the increasing demand of fuels, extraction values for both policy cases are similar. Oil demand in BAU_Const_O scenario would be 37% lower than BAU scenario by 2050. In this same year, remaining reserves would reach values of 800–860 MBbl (Fig. 2 c)). Oil savings in OS policy does not have a significant effect on national oil availability in the forthcoming years.

Given that refining capacity and yield remains static Ecuador will have the same mix of refining outputs as of today: fuel oil as the main product (around 49%), followed by diesel oil (23%), gasoline (18%), and others (LPG, jet fuel, non-energy, and refinery gases with 11%). Currently, fuel oil production is around three times national demand, while diesel and gasoline national production only covers 40% of demand in both cases. Ecuador will keep exporting crude oil that cannot be refined locally and import petroleum products, maintaining what we have called "foreign refinery" of its crude oil production.

If current trends for energy intensity and use of final sources continue, the predominance of petroleum products in the energy mix for Ecuador will be maintained and there would be an ever-increasing gap between demand and national production (Fig. 3 a)-b)). Moreover, in the case of BAU_Const_2P scenario, oil available for Ecuador at global level would start to be insufficient by 2036 (while the Ecuadorian share in global demand remains constant, oil supply diminishes due to physical constraints), and the already limited production of the most demanded petroleum products will decline.

4.1.2. Electricity

Fig. 4 a), c), and e) depict installed capacity for electricity generation in the period under analysis for each scenario. Leaps in installed capacity in years 2016, and 2028 are due to introduction of large, planned hydropower projects (1500 MW, and 1200 MW, respectively). After this, capacity addition is to follow inertial growth trends. To cope with an increasing demand of electricity that would partially replace fossil fuels, another leap is expected by 2046. For BAU scenario, electricity supply infrastructures would increase by almost 1.6-fold by 2050 with relation to 2020 values. For BAU_Const_2P and BAU_Const_O scenarios, installed capacity would be 13%, and 10% shorter, respectively, compared to BAU due to the reduction in economic activity. and electricity demand. Among all sources in the mix, hydro presents the most notorious increment in the period 2020–2027 for al scenarios. Hydropower capacity would increase by 46% (from 5072 MW to 7417 MW). Aligned with an increasing demand of electricity, from 2028 onwards, hydropower capacity would continue to grow reaching values of 12,864 MW by 2050 for BAU, 12,418 MW for BAU_Const_2P, and 12,622 MW for BAU_Const_O. Regarding the rest of renewables, they present marginal values in installed capacity compared to hydro. Solar PV capacity by 2050 would reach 2787 MW, 2235 MW, and 2465 MW, for BAU,



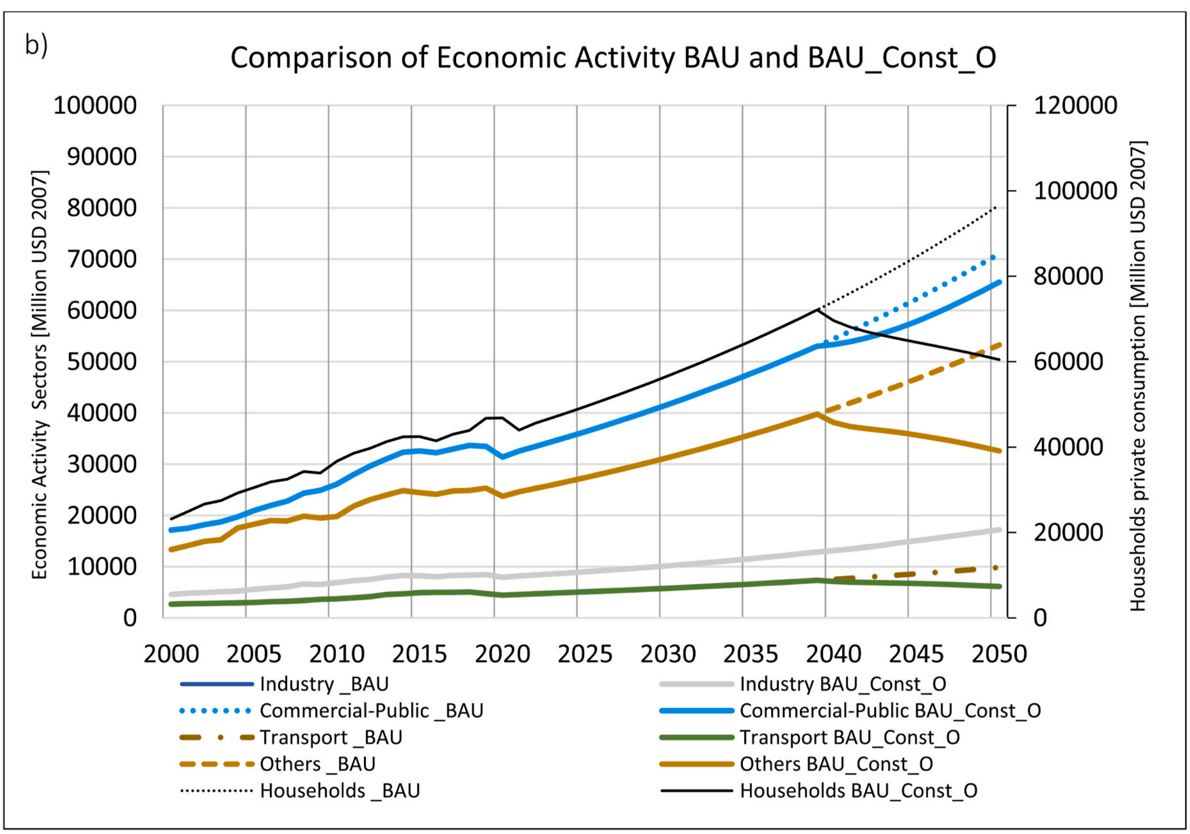


Fig. 9. Comparison of the evolution of economic activity per sector with BAU scenario a) BAU_Const_2P, and b) BAU_Const_O.

BAU_Const_2P, and BAU_Const_O, respectively, followed by on shore wind (429 MW, 412 MW, and 420 MW), biomass (127 MW for all scenarios) and biogas (6.4 MW for all scenarios). Installed capacity of NRE by 2050 would reach 5906 MW in BAU, 3976 MW in BAU_Const_2P, and 4332 MW in BAU_Const_O.

Renewables in electricity generation have a key role in covering demand as seen in Fig. 4 b), d), and f). On average, electricity share from renewables would reach 80% from 2020 to 2050 for all three scenarios. From 2027 to 2034, RES capacity is large enough to cover more than 90% of electricity demand, which reduces NRE electricity during the same time frame. After 2034, increasing electricity demand will not be covered by inertial increment of RES, and electricity from NRE would rise its share to up to 30% by 2050 for BAU, 22% for BAU_Const_2P, and 24% for BAU_Const_O. If current expansion plans are implemented and development of installed capacity is maintained, projected electricity demand would be fully covered in all scenarios. Nevertheless, there is still a vast potential of hydro and solar PV available that could be used for a more ambitious expansion.

4.2. Energy demand

Energy demand per sector for each scenario is depicted in Fig. 5 a), c), and e). Total energy demand for BAU scenario in 2050 will be 2.37 times its value in 2020 with an average yearly growth of 2.9%. In contrast to BAU, total energy demand in 2050 would be 40% and 33% lower for BAU_Const_2P and BAU_Const_O scenarios, respectively This reduction on demand in constrained scenarios respect to BAU would start in 2038 and indicates the effects of scarcity on energy intensity and source substitution, and the reduction of oil and petroleum products supply that provokes a contraction in economic activity.

Industry demand would grow on average 3% per year for BAU scenario, 2.8% for BAU_Const_2P, and 2.9% for BAU_Const_O. Demand for Commercial-Public would increase at a rate of 4.0% in BAU, 3.3% in BAU_Const_2P, and 3.7% in BAU_Const_O. By 2050, demand in this sector would be 19.7%, and 9.3% lower respect to BAU.

Transport sector would increase its demand 2.7% per year on average in BAU scenario. This trend would be maintained in BAU_Const_2P until 2038 and after this year an average decay of 2.9% is foreseeable. For BAU_Const_O, decay would start in 2039 with yearly rates of 1.8%. By 2050 Transport demand would be 48%, and 38% lower compared to BAU. Nevertheless, this sector takes the largest share in demand for all scenarios reaching values from 28% to 33% by 2050.

Households demand would grow on average 2.5% per year for BAU scenario. Regarding BAU_Const_2P and households demand would increase as in BAU until 2038. After this year demand would tend to decrease due to scarcity of petroleum products 2.6% per year. BAU_Const_O scenarios depicts a peak on households' demand in 2039, and after this an average yearly decay of 1.6%. It is worth to highlight that "Others" sector, which is the sum of small sectors compared to transport, commercial, industry and households, has the highest growth rate (3.5%) in BAU scenario. However, BAU_Const_2P and BAU_Const_O scenarios show a change of behavior in 2038–2039 due to national and global oil constraints and demand of this sector would be 53% and 44% lower compared to BAU. The evolution of energy demand indicates the vulnerability that sectors with a high share of petroleum products would have towards a potential energy scarcity in the future, that would start around 2038 for BAU_Const_2P, and 2039 for BAU_Const_O.

The evolution of the energy intensity show that the country has not improved energy efficiency in past decades since most energy intensities remain constant or even increase (Fig. 5 b). However, if global constraints are applied (Fig. 5 d), f)), energy intensity would tend to improve starting in 2040 for both scenarios compared to BAU. Reductions in energy intensity from 2020 to 2050 would reach rates from 0.5% to 2.4% depending on the sector.

Diesel and gasoline, remain the principal final sources in BAU scenario (Fig. 6 a) with an average yearly growth of 3.0% and 2.7%, respectively. BAU_Const_2P and BAU_Const_O scenarios (Fig. 6 b)-c) depict a growth rate for gasoline of 0.8% and 1.2% respectively, and rates of 0.6%, and 1.1% for diesel. Compared to BAU, gasoline demand by 2050 for BAU_Const_2P and BAU_Const_O would be 48%, and 40% lower, respectively. Regarding diesel, demand would be 46%, and 38% lower. Electricity is the third most used source with growth rates of 4.2% for BAU, 3.4% for BAU_Const_2P and 3.5% for BAU_Const_O. Its share in the mix would increase from 17% in 2020 to 26% in 2050 for BAU, 34% for BAU_Const_2P, and 32% for BAU_Const_O. This indicates that restrictions in oil and petroleum products supply would pressure the system to find a more abundant energy source to use, in this case electricity.

The scenarios developed under BAU narrative depict that even if the evolution of energy intensity in most sectors show constant or lower values, future energy demand would substantially increase driven by the expected economic growth until 2038. After this, energy availability starts to decrease causing a contraction in economic activity, and consequently in energy demand.

4.3. Indicators for oil

The diagrams in Fig. 7 offer a picture of present and future scenarios of Ecuador trade of crude oil and petroleum products for BAU_Const_2P (7 b), and BAU_Const_O (7 c) scenarios.

Fig. 7 a) shows the current situation dominated by national oil extraction that is diverted in a good extend to foreign refinery that covers national demand of oil products, since 52% of the exports return as petroleum product imports. This leaves only a 41% of net oil exports.

The panorama in 2050 for BAU_Const_2P scenario (Fig. 7 b)) is dominated by imports of both oil and petroleum products which are limited and caused a reduction in economic activity. For BAU_Const_O scenario (Fig. 7 c)) oil availability allows to maintain production from national refinery but most of the demand of petroleum products must be fulfilled by imports which are still insufficient. LPG, gasoline, and diesel oil, the most demanded and imported fossil fuels will have the sharpest declines in demand.

Gross oil exports for BAU_Const_2P (Table 5) indicate that OS policy would not delay exports decline, and by 2030 Ecuador would have lost its status of oil exporter. For BAU_Const_O scenario, gross exports present a smoother decline, but they would still fall to zero by 2050 even if OS policy is implemented. Net oil exports indicate that oil embedded in petroleum product imports would surpass oil exports by the end of this decade considering both scenarios and Ecuador would be exporting less oil than imports in form of petroleum products.

4.4. Fossil fuels trade balance

Oil export policies assessed do not present different oil extraction profiles for BAU_Const_2P scenario. Furthermore, for BAU_Const_O scenario OS policy does not have a representative effect for delaying extraction decay and depletion of reserves. Therefore, trade balance has been assessed considering only Maximum Exports (ME) policy for both scenarios and the three fossil fuel prices projections from IEA. Fig. 8 a) shows that for BAU_Const_2P and SP oil price trade deficit would start in 2030 and continue to increase until 2041. After this year trade deficit is reduced, which shows the effect of scarcity on imports and the pressure to reduce economic activity. For BAU_Const_O (Fig. 8 b), trade surplus would be maintained up to 2032, and contrary to BAU_Const_2P trade deficit would increase until 2050. However, it would be around 2.3 billion USD shorter.

If oil prices follow SD, trade deficit would also start in 2025 for BAU_Const_2P. Regarding BAU_Const_O, trade surplus would be maintained until 2030 and trade deficit difference compared to BAU_Const_2P would be around 1.2 billion USD by 2030. Compared to SP, lower oil prices, would result in a shorter deficit (around 4.1 billion USD for BAU_Const_2P and 3 billion for BAU_Const_O) by 2050.

DR price depicts a similar behavior to SD in terms on trade balance decay. If BAU_Const_2P is considered, trade deficit starts in 2025 as well. Under URR O, ME policy would have the same effect as in SD regarding the year at which economic trade deficit starts. The difference in deficit between URR O and URR 2P would reach 4.4 billion USD by 2050.

4.5. Emissions and energy transition indicators

Emissions from final energy demand, and carbon intensity for constrained scenarios are depicted in Table 6. The predominance of petroleum products in the final energy mix, along with an increasing economic activity would produce an average annual increase of emissions of 2% for both constrained scenarios.

Emissions per unit of final energy would decrease by 18% in 30 years at average rates of 0.8%, and 0.7% for BAU_Const_2P, and BAU_Const_O scenarios, respectively. Reduction in final carbon intensity might be in part attributed to an increase in electricity share in final demand. Regarding power carbon intensity, a significant reduction would be achieved by 2030 and it would remain relatively constant up to 2034. From 2035 onwards emissions would increase above 178, and 197 $TonCO_{2eq}$/GWh by 2050 for BAU_Const_2P, and BAU_Const_O scenarios, respectively, given the increment in electricity generated from fossil fuels.

4.6. Expected growth and degrowth

Constrained scenarios depict adjusted values of economic activity to avoid energy supply deficits, which would start by 2038, (Fig. 9). Industry would continue to grow in BAU_Const_2P and BAU_Const_O scenarios as in BAU scenario. Scarcity of petroleum products would barely affect given that their share in this sector would tend to decrease (from 21% in 2038 to 5% in 2050). Regarding Commercial-Public, economic activity might increase at average rates of 1% and 2% for BAU_Const_2P and BAU_Const_O scenarios, respectively. In this sector the share of petroleum products decays from 36% in 2038 to 28% in 2050.

Transport is the sector that would register the largest reduction in economic activity with average decay rates of 2.8% and 1.3% for BAU_Const_2P and BAU_Const_O scenarios, respectively. Transport has an average share in total demand of petroleum products of 40% from 2038 to 2050, which explains the sensitivity towards scarcity of these fuels. Moreover, energy demand in transport is dominated by oil products (97% on average).

"Others" sector would register a similar rate of decay in economic activity to transport (2.6% and 1.2% for BAU_Const_2P and BAU_Const_O scenarios). In this sector, petroleum products cover 94% of the demand. Likewise, the share in petroleum products total demand is 20% on average. Regarding Households private consumption, it presents similar trends to others sector with average decay rates of 2.6% and 1.2% for BAU_Const_2P and BAU_Const_O scenarios, respectively. If energy used by vehicles is considered, petroleum products have a share of 69% in households' demand. In terms of total demand of petroleum products this sector takes 19% on average.

5. Discussion

If present trends are maintained, in the next three decades Ecuador will demand almost 2.4 times more energy than today. Transport would remain as the most energy demanding sector, and its intensity does not show a downward trend given that alternative, more efficient technologies (hybrid, electric) have negligible shares in a BAU context. This draws a worrying trend of fossil fuels dependency for the country, aggravated by the decline in oil extraction and oil imports. Policies analyzed for oil exports would have very slight, or negligible effects in delaying oil extraction decay. Even an aggressive policy as OS would not be enough to offset the progressive reduction of oil availability.

Oil scarcity would limit national production of petroleum products, which would increase the gap between supply and demand. The most optimistic case of national oil availability would not avoid deficits in energy supply that would cause a contraction in economic activity. If more ambitious policies are not implemented, the Ecuadorian energy system would not be capable enough to reduce energy use through improvement of energy efficiency and source substitution to avoid shortages.

Power capacity expansion, supported mainly on hydropower [49] will make electricity the most suitable energy source to replace fossil fuels. Availability of electricity to replace fossil fuels in final demand would have a positive effect in reducing emissions. However, development of hydropower and renewables such as solar PV and wind under current trends will not be enough to cover electricity requirements, and generation from NRE would regain participation in all three scenarios. To cut dependency on fossil fuels and cover potential demand from an increasing use of electricity as alternative energy source, it is important to foster even more the development of electricity from renewables given the large potential of hydro and solar PV.

The limited refining capacity and ever-increasing demand indicate that global limits are key factors to consider due to the high dependency on fossil fuels imports to satisfy demand in the future. It is evident then, that disruptive scenarios must be tested to analyze the combined effects of more aggressive policies and oil availability towards an imminent energy transition without compromising economic growth.

It is important to develop and promote policies addressed to reduce dependency on oil as energy and revenue source. Improvements in final energy use, high penetration of renewables along with massive displacement of petroleum products by electricity in all economic sectors, especially transport would be a key strategy to follow the path towards an energy transition. These policies must take effect in the short or medium term to avoid a collapse in Ecuador economic and energy systems.

6. Conclusions

A system dynamics model has been developed to analyze energy supply and demand pathways under scenarios of oil availability up to 2050 for a small oil producing country. When applied to the Ecuadorian context, the model permits to identify under a BAU scenario energy demand will double by 2050.

When national and international physical constrains for fossil fuel supply are considered, the system might not be able to avoid imbalances in supply and demand of fossil fuels; that will start to occur in 2038. Shortages in petroleum products supply would cause contraction in economic activity with GDP values 28%, and 20% lower compared to BAU scenario mostly in sectors with high dependency on these fuels. The more oil available to satisfy demand, the less the system will pressure to improve energy efficiency and replace scarce sources with more abundant ones. Nevertheless, a higher availability of oil would avoid a deeper collapse in the economy. Electricity from hydropower, NRE, wind and solar PV might partially replace scarce petroleum products supported.

Limited refining capacity, along with limited access to oil and petroleum products would increase the gap between supply and demand. Results obtained indicate that disruptive scenarios with ambitious policies for energy efficiency, deployment of renewables combined with oil availability must be analyzed to avoid scarcity of energy sources and potential decay of economic activity.

This work aims to provide a panorama of a small oil producing country's energy future under BAU narrative scenarios, it has not studied ambitious policies of efficiency improvement or energy transition. Future work should be focused on integrating all these energy policies. In the case of Ecuador, transport sector must have special attention given its role as the biggest consumer of fossil fuels.

Credit author statement

Vicente Sebastian Espinoza: Data curation, Formal analysis, Investigation, Writing – original draft. Javier Fontalvo: Data curation, Writing – original draft. Jaime Marti-Herrero: Conceptualization, Writing – review and editing, Supervision. Luis Javier Miguel: Conceptualization, Supervision, Writing – review and editing. Margarita Mediavilla: Conceptualization, Supervision, Methodology, Writing – review and 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2022.124963.

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