Supplementary Material

Abstract

The present document presents the supplementary material for the article Energy transition scenarios for fossil fuel rich developing countries under constraints on oil availability: The case of Ecuador Section 1 presents the structure of the Ecuadorian Energy Development under Energy Constraints model (EEDEC), including drivers used to represent energy demand growth, and oil and natural gas availability. Section 2 depicts the definition of scenarios.

1. Structure of EEDEC model

For the development of the system dynamics model of the Ecuadorian Energy System the structure of the National Energy Balance of 2017 was used as basis, which comprises the supply, transformation and consumption of primary and secondary energy sources. This structure aligns itself with the proposal of the Manual of Energy Statistics issued by the Latin-American Organization of Energy OLADE, as detailed hereunder:

Activities

Supply

- Production/Extraction
- Imports
- Exports

Transformation

- Refineries
- Electricity Plants
- Auto-producers
- Gas Works
- Distilleries

Consumption

- Industry
- Transport
- Commercial, Public Services
- Residential
- Other sectors (Self-consumption, agriculture, fishing, mining, construction, Others)

Sources

Primary

- Crude oil
- Nonassociated Natural Gas

- Associated Natural Gas
- Hydro
- Wood
- Sugarcane products
- Other primary sources (Solar, wind, biogas, geothermal)

Secondary

- Electricity
- Liquefied Petroleum Gas
- Gasoline
- Kerosene-Jet Fuel
- Diesel Oil
- Fuel Oil
- Gases
- Non-energy products
- Alcohol (Ethanol)

The model will have a temporality corresponding to the 2000-2050 period. The historical information of energy supply, transformation and demand pertains to the 2000-2017 period and was obtained from the National Energy Balance of 2017.

1.1. Dynamics of energy intensities

Energy intensity is an indicator and a fundamental variable for the energy prospective models and for the present model. In general, energy intensity is expressed as the ratio between energy consumption and an economic indicator, usually the Gross Domestic Product (GDP) or the Gross Value Added (GVA). With the goal of disaggregate this indicator, the energy intensity of each sector described by the model was estimated, with the energy intensity by sector and energy source (i, k) being determined dividing the energy consumption (i, k) by the GDP of each sector (k). Here k are the sectors (Industry, Transport, Commercial-Public Services, Residential, and Others), and i are the final energy sources (both primary and secondary sources). In total, 65 (13x5) energy intensities are obtained. In order to collect both energy and economic data, the National Energy Balance of 2017 was used. The sectorial energy intensities were disaggregated by final use source. The developed sub-models were *EI by source and sector* and *EI by source Households,* with the work developed by Blas et [1] al being used as reference.

The behavior of the energy intensity is dynamic, that is, it changes with time. For a given energy type and sector, the energy intensity varies mainly as consequence of:

a) Technology changes that bring on variations in energy efficiency, for example motors with better performance, better thermal isolation in heating systems, appliances with a reduced energy consumption, among others. Energy intensity can also increase due to the loss of efficiency in a technology change that responds to other criteria than energy optimization.

b) Technology substitutions that imply a change of the final energy source. This substitution can be caused by many different factors between which can be counted a technological necessity, an energy policy, among others. In the case of the substitution of a type of energy by another, one energy intensity increases, while the other one decreases.
c) Variations in the GDP (or sectorial GVA) due to factors external to energy, which are not included in this model.

A simplified version of the structure of the modelled dynamics of the energy intensities is depicted in Figure S1.

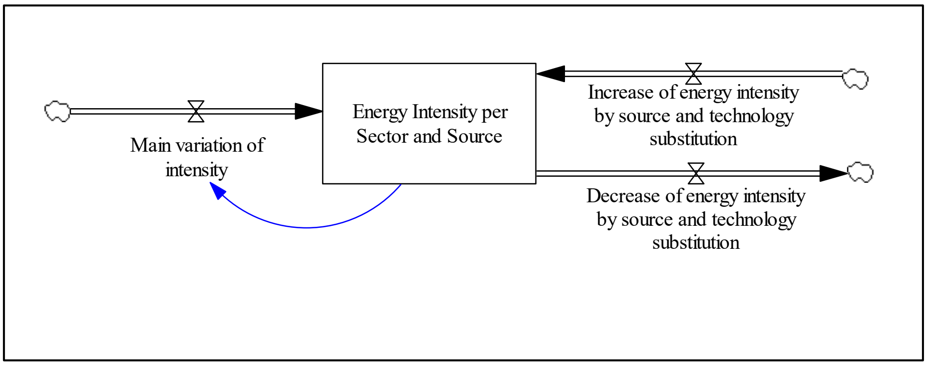

Figure S.1. Basic structure of the dynamics of the Energy intensities of the Ecuador model

Conceptually, the fact that Energy Intensity is a level variable can be explained as the result of the historical accumulation of knowledge and capital oriented toward the exploitation of energy to obtain an economic gain. The main variation of the energy intensity is assumed, at first, to respond to an inertial tendency based in historical data. To model the inertial trend 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 annual relative variation. This is the baseline trend $(\overline{\Delta EI_{\iota k}{}^{h}})$ which is the first component that describes the evolution of energy intensity (See Table S.1).

Table S.1. Values of $(\overline{\Delta EI_{\iota k}{}^{h}})$ per source and sector

Sector	***Source***												
	Oil	**Natural Gas**	**Wood**	**Sugar Cane Bagasse**	**Electricity**	**LPG**	**Gasoline**	**Kerosene**	**Diesel Oil**	**Fuel Oil**	**Gases**	**Non Energy**	**Ethanol**
Industry	-	0.9397	0.9741	0.9690	1.0600	1.0550	0.9667	-	0.9749	0.9292	-	-	-
Commercial-Public	-	-	-	-	1.0378	1.0002	0.9777	-	1.0134	1.0002	-	-	-
Households	-	1.1897	0.9308	-	1.0205	0.9949	-	0.7051	-	-	-	-	-
Transport	-	-	-	-	0.9667	0.9399	1.0202	0.9996	1.0268	0.9873	-	-	-
Others	0.9867	-	-	-	0.9676	1.0112	1.0597	1.1328	1.0512	0.9654	0.9337	1.0109	-

Assuming that inertial tendencies continue in the future and the model is carried out in exponential form, several problems arise. The first difficulty is that, as intensity increases, that is, for positive variations, the intensity in the future exhibits exponential growth. To avoid this behavior, we assume that in the cases where the variation of the intensities is positive, growth is linear instead of exponential.

Another drawback that emerges is that, in those cases where the variation of the intensity is negative, and as result the intensity decreases, the obtained results are near zero. For this reason, a limit in the global intensity is set up under which a sectorial intensity can never have a value. This threshold corresponds to a percentage of the intensity in 2017. In Figure S.2 it is shown the modelling structure of the inertial variation of the energy intensity, and how this one is affected by a limit that prevents it to go below certain value through the usage of the variables highlighted in red.

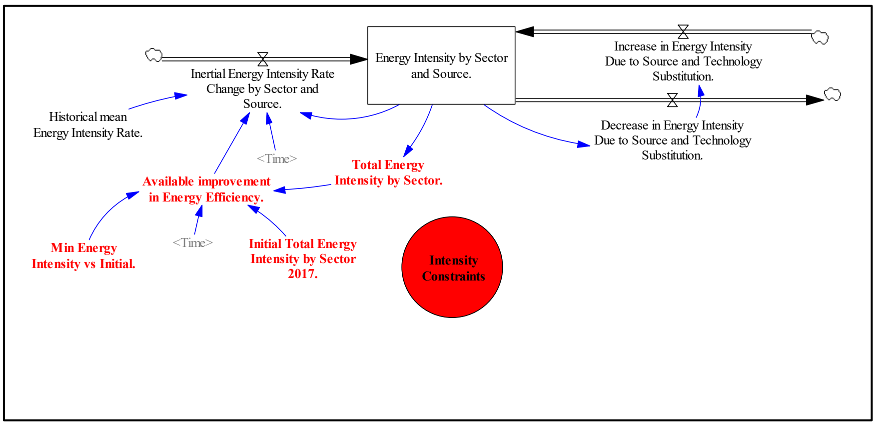

Figure S.2. Basic structure of the dynamics of the inertial variation of the energy intensity in the EEDEC model

Trends in energy intensity may have variations in the future for two factors:

- Variation in energy intensity attributed to the implementation of energy efficiency measures for the current technology and sources used in each sector $\left(\Delta EI_{ik}{}^{eff}\right)$.
- Variation in energy intensity attributed to source substitution $\left(\Delta EI_{ik}{}^{sub}\right)$. In this case the intensity of the source to be replaced decreases and the one that replaces the first increases. The total variation of energy intensity per sector and source is shown in Eq. (A.1).

$$\Delta EI_{ik} = \overline{\Delta EI_{ik}}^{h} + \Delta EI_{ik}{}^{eff} + \Delta EI_{ik}{}^{sub} \qquad (A.1)$$

Following the methodology used as reference, there are two main aspects that drive the variation of energy intensity (Eq. A.2 and A.3): the first one involves market factors associated to the scarcity of each energy source k (perception of scarcity PS_k), which would lead to improve energy intensity or fuel substitution. This factor reflects energy supply (FES_k)- demand (FED_k) imbalances due to the dynamics of natural resources extraction and its physical availability and import-export policies. This is an alternative perspective that considers physical scarcity of energy sources instead of energy price. The imbalance in supply and demand is depicted as Abundance of each energy source. The second aspect gathers policies (Policy Effects) that foster energy efficiency of current sources used in economic sectors as well as fossil fuels substitution. For variation of intensity due to efficiency and fuel substitution, maximum variations have been obtained based on historical data and the method used in de Blas et al [1], and are depicted in Table S.1.

$$\Delta EI_{ik}{}^{eff} = \left(PS_k + Policy\ Effects^{eff}\right) * Max_{ik}^{eff} \qquad (A.2)$$

$$\Delta EI_{ik}{}^{sub} = \left(PS_k + Policy\ Effects^{sub}\right) * Max_{ik}^{sub} \qquad (A.3)$$

All sectors in the economy need energy to generate outputs. For this reason, efficiency, and source substitution present physical and thermodynamic limits [2–4]. This means that energy efficiency improvements may slow down in the medium or long-term and energy intensity in each sector may reach a minimum positive value. Considering the uncertainty that these limits may have [1], it has been used a reference the value of 30% compared to levels of 2017, as used in MEDEAS for all sectors.

The variable perception of scarcity follows the dynamics described in de Blas et al [1]. (Eq. A.5), cumulatively increasing its value when demand exceeds supply and decreasing if no shortages are registered. It depends as well on the actual scarcity of energy source k (Eq. A.4), the sensitivity to scarcity (*SS*) that sectors and households may have, and the time that takes to disregard scarcity (Forgetting Factor *FF*).

$$Scarcity_k = \frac{FED_k - FES_k}{FED_k} \qquad (A.4)$$

$$PS_k(t) = Scarcity_k * SS + \frac{PS_k(t-1)}{FF} \qquad (A.5)$$

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.

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

Where:

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

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

$Share\ Total\ Demand_{ki}$: 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

EI_{ki}: Is the energy intensity of energy source k, for sector i.

Figure.A3 depicts the causal diagram of energy scarcity and Figure S4. depict the structure of the dynamics of energy scarcity.

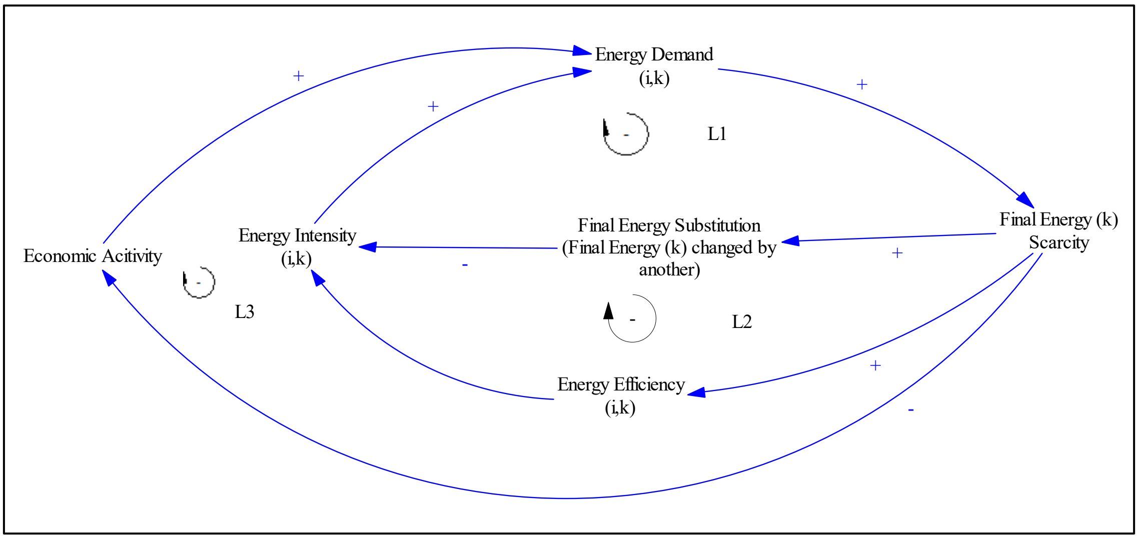

Fig A3. Causal loop diagram of the effects of energy scarcity of energy source k in sector i in EEDEC model.

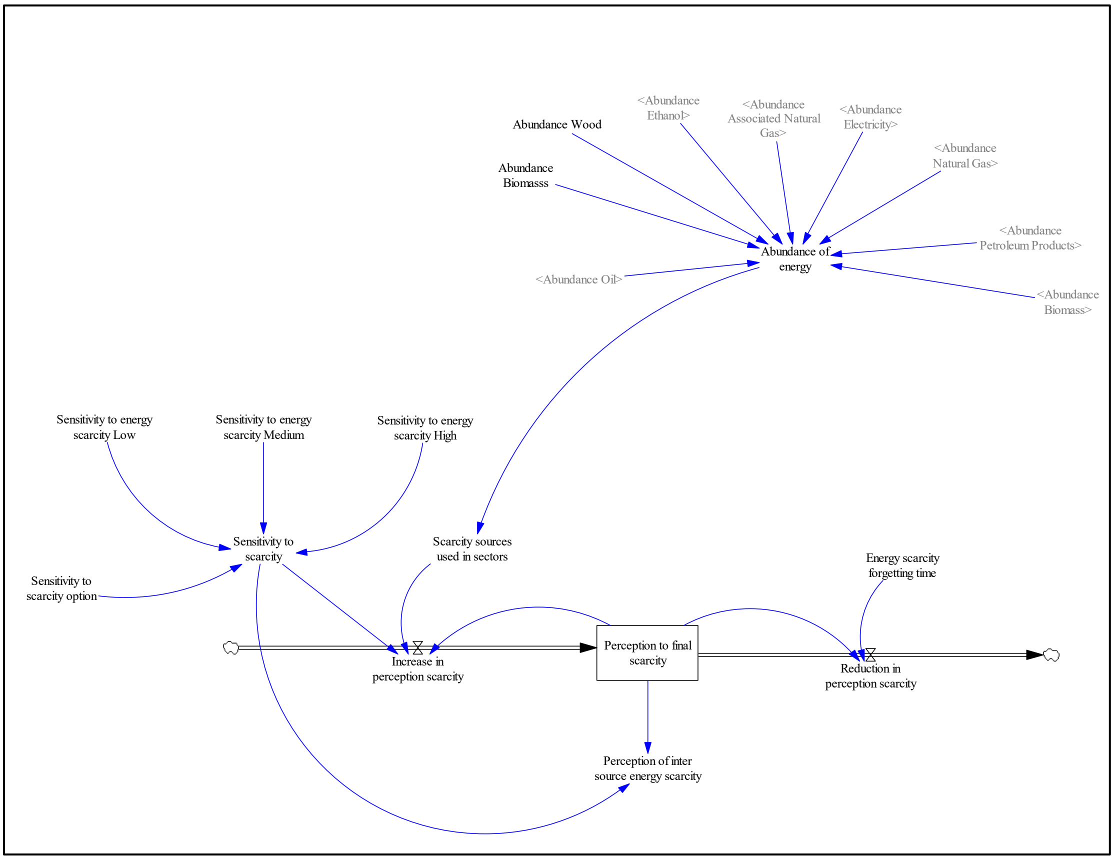

Figure S.4. Structure of the dynamics of energy scarcity in EEDEC model.

Acceleration of the energy efficiency will be bounded by an annual maximum factor of improvement for the intensity of each sector. In the case of the variables Max_{ik}^{eff} andMax_{ik}^{sub}, the calculated historic annual intensities were used as basis, and their variation $\Delta EI_{ik}^{h\ eff}$ was determined. In order to obtain the variation of the energy intensity due to improvements in the efficiency $\Delta EI_{ik}{}^{eff}$ and sources substitution$\Delta EI_{ik}^{h}{}^{sub}$, it was assumed that the variation in the intensity of each replaced source with respect to the variation of the total intensity for each sector ΔEI_{k}^{h}, is compensated by the diminution in the energy source replacing the first one, as stated in equation (A.7).

$$\sum_{i=1}^{13}\left(\Delta EI_{ik}^{h}{}^{eff} - \Delta EI_{k}^{h}\right) \approx 0 \tag{A.7}$$

Whereby,

$$\Delta EI_{ik}^{h}{}^{eff} = \Delta EI_{k}^{h} \tag{A.8}$$

$$\Delta EI_{ik}^{h}{}^{sub} = \Delta EI_{ik}^{h} - \Delta EI_{k}^{h} \tag{A.9}$$

Variables $\Delta EI_{ik}^{h}{}^{eff}$ y $\Delta EI_{ik}^{h}{}^{sub}$ are modelled as random variables with a probability distribution function defined by its mean and variance: $\mu(\Delta EI_{ik}^{h}{}^{eff})$, $\sigma^2(\Delta EI_{ik}^{h}{}^{eff})$, y $\mu(\Delta EI_{ik}^{h}{}^{sub})$, $\sigma^2(\Delta EI_{ik}^{h}{}^{sub})$.

The maximum values used in the model depend on the means and variances for a given confidence interval, as shown in Table S.2 and Table S.3.

$$Max_{ik}^{eff} = \sqrt{\frac{\sigma^2(\Delta EI_{ik}^{h}{}^{eff})}{n\times(1-\alpha)}} \tag{A.10}$$

$$Max_{ik}^{sub} = \sqrt{\frac{\sigma^2(\Delta EI_{ik}^{h}{}^{sub})}{n\times(1-\alpha)}} \tag{A.11}$$

Where the confidence interval (α) is 90%.

Table S.2. Maximum annual variations of the energy intensities by energy efficiency improvement

Sector	$\boldsymbol{Max_{ik}^{eff}}$
Industry	9.74%
Commercial-Public	4.32%
Households	2.02%
Transport	5.13%
Others	7.66%

Table S.3. Maximum annual variations of the energy intensities by substitution of one type of final energy by another Max_{ik}^{sub}

Sector	***Source***												
	Oil	**Natural Gas**	**Wood**	**Sugar Cane Bagasse**	**Electricity**	**LPG**	**Gasoline**	**Kerosene**	**Diesel Oil**	**Fuel Oil**	**Gases**	**Non Energy**	**Ethanol**
Industry	-	15.45%	8.66%	27.06%	7.13%	15.63%	28.35%	-	13.01%	11.73%	-	-	-
Commercial-Public	-	-	-	-	3.39%	4.07%	12.46%	-	4.03%	4.18%	-	-	-
Households	-	45.77%	1.60%	-	1.41%	1.11%	-	13.20%	-	-	-	-	-
Transport	-	-	-	-	5.01%	16.27%	12.92%	15.58%	4.26%	16.57%	-	-	-
Others	7.49%	-	-	-	16.78%	26.01%	11.39%	71.46%	23.67%	8.19%	19.08%	12.50%	-

The pressure exerted by the policies will depend on the year they are implemented and the speed of application. The pressure exerted by the energy price will depend on the perception of source scarcity. The variables for policies implementation are highlighted with green color in Figure S.5 a). The year of implementation of the policies, their conclusion year, and their speed of application can be defined for each sector in the intensities board.

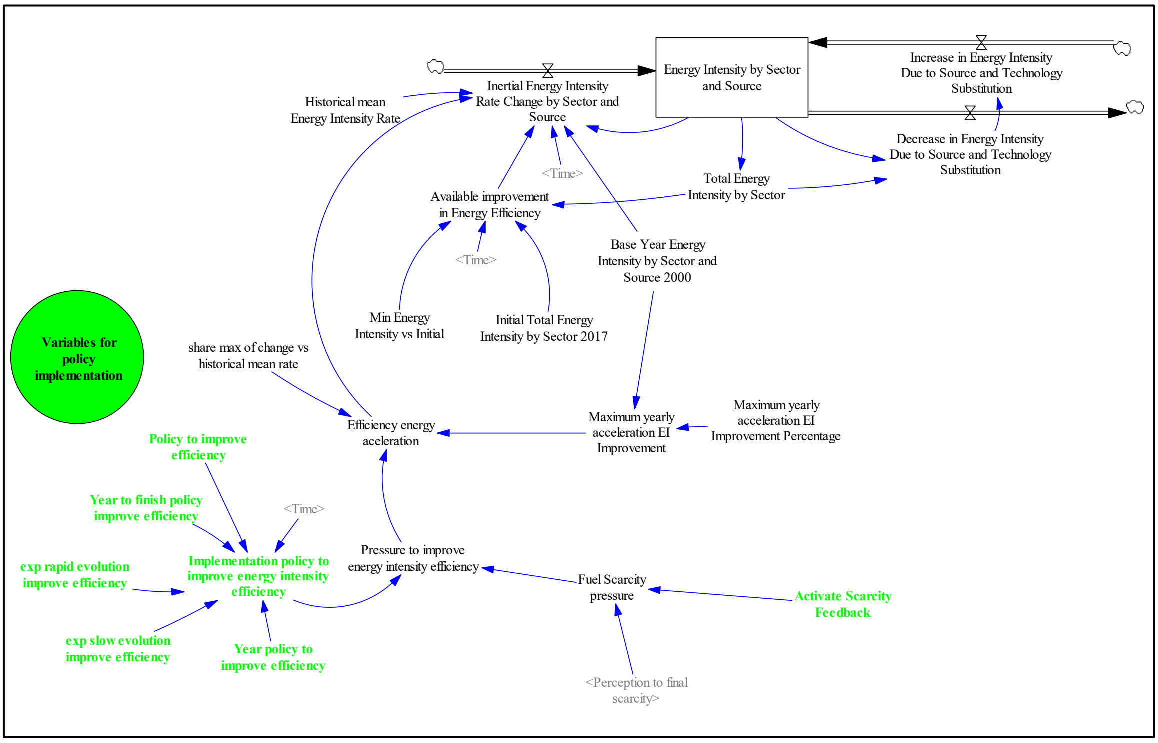

Figure S.5. Implementation of variables of policies for the improvement of energy intensity in the model EEDEC

To model the Exchange between final energy types in a determined sector, the following variables are used for each of the 4 sectors plus the ones corresponding to households.

A 13 x 13 matrix for each sector:

Matrix of change in energy efficiency between energy types for a sector

When a technology based on a specific energy type is replaced by one based on another energy type, it is foreseeable the energy quantity necessary to obtain the same economic value of products and services will also change. Thereby, if 1TJ of an energy type (i) is substituted by another energy type (j) that requires 1.4 TJ, a decrease of 0.05 TJ/$ in the energy intensity of type (i) will entail an increase of 0.07 TJ/$ in the energy intensity of type (j). In this case the coefficient of this matrix in the (ij) position will be 1.4, and the one in the (ji) position will be its inverse 1/1.4 = 0.71.

Two 13 x 1 vectors for each sector:

Vector of minimum energy of each final source, which must be used in each sector as it is non-substitutable in parts per unit.

Vector of maximum possible annual change for a type of energy in a sector X in parts per unit. Thus, if the element i of the vector has a value of 5%, it means that with the appropriate conditions each year, for the sector X, it would be possible to substitute up to the 5% of the consumed energy of the type I, using the values of Max_{ik}^{sub} in Table S.3.

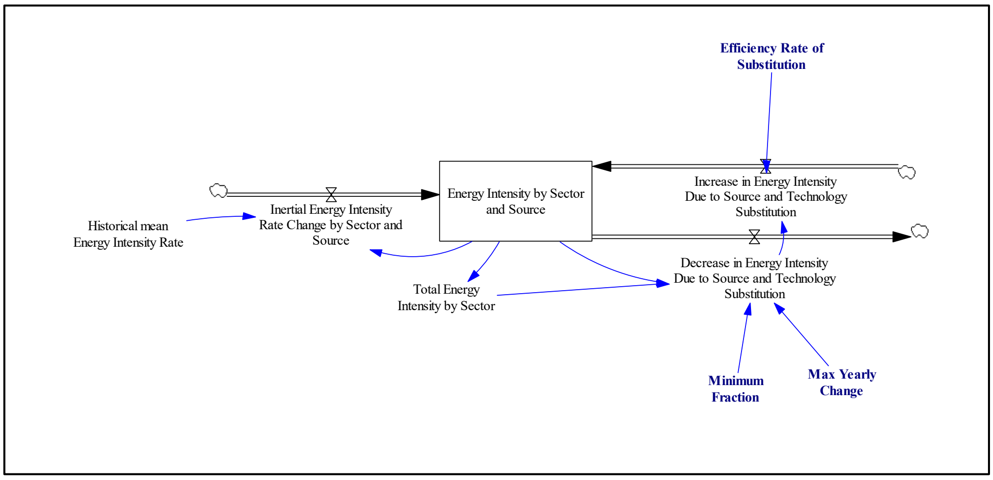

Figure S.6. Variables related to the change in energy intensity due to substitutions in technology and energy source

As in the case of the acceleration in the variation of energy efficiency, this technology change that implies the substitution of a type of energy by another is due to two reasons:

i. The availability of different energy sources. If a type of final energy is scarcer in the market and this leads to the increase in its price, it should lead to a technology pressure toward the substitution of that energy source by a more abundant one.
ii. Policies that promote the mentioned change, that could be related to climate change mitigation, energy security, or another national priority.

The pressure exerted by these policies will depend on the year that they are implemented as well as the speed of application. Whereas the pressure exerted by the scarcity of a type of energy will depend on the relative abundance of that source with respect to the other sources.

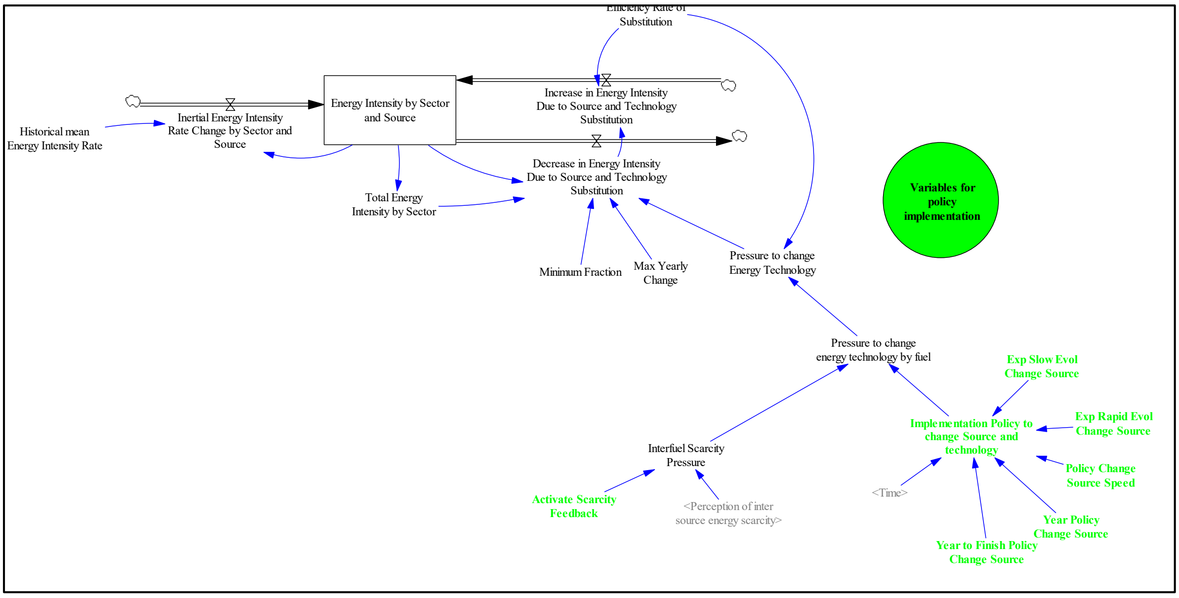

Figure S.7. Variables related to the change in energy intensity due to substitutions in technology and source

The variables of implementation of policies like the ones described beforehand, are the efficiency rate, maximum annual variation, and minimum fraction of the energy type, and are defined for each sector in an intensity matrix. The general model, including the inertial variation and changes in technology and source, is depicted in Figure S.8.

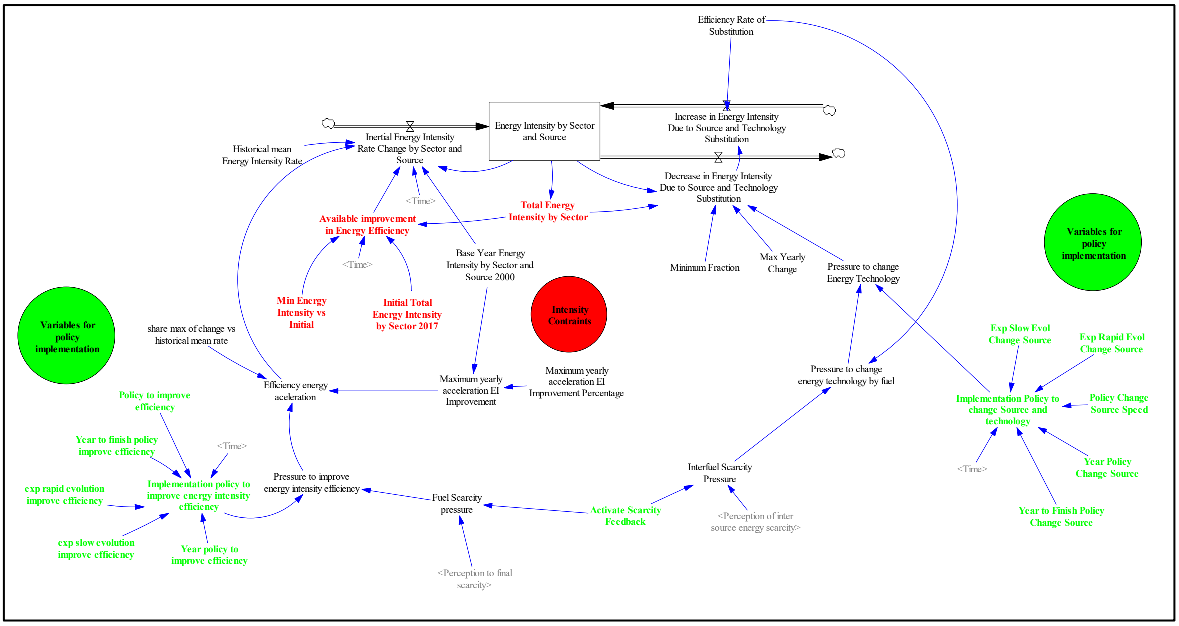

Figure S.8. Structure of the general modelling of the dynamics of the energy intensity in the EEDEC model

1.1.1. Top-Down Approach

The modelling methodology that has been described up to this point corresponds to a Top-Down approach, where the energy intensities of each sector are modified in a global fashion, without deepening in specific variables. In the Top-Down approach, the following set of hypotheses is assumed:

1. The model reflects in a predominant way the historical tendency of the intensities.
2. Besides the historical tendency, two additional factors are included:
   a. Change in intensity due to the replacement of a technology for another that uses a different final energy. This change is at the same time driven by two leading forces:
      i. Scarcity of the energy source, which translates into a larger price of the same source.
      ii. Policies that promote the substitution due to climate change mitigation, energy security, among other reasons.
   b. Improvement in energy intensity due to the pressure exerted by:
      i. Increase in the price of that type of energy
      ii. Energy efficiency policies
3. Limits in technology changes and in efficiency improvement are established

In this approach, in order to develop scenarios with different evolutions in the energy efficiency of each sector, the policies and the limitations in technology changes are modified within an intensities panel in an exogenous manner, as shown in Figure S.9:

	Industry												
	Oil	Natural Gas	Wood	;ar Cane Produ	Electricity	LPG	Gasoline	Kerosene	Diesel Oil	Fuel Oil	Gases	Non Energy	Ethanol
Improvement of efficiency policies													
Start year policy	2020	2020	2020	2020	2020	2020	2020	2020	2020	2020	2020	2020	2020
Speed policy	3	3	3	3	3	3	3	3	3	3	0	0	0
Maximun yearly aceleration of energy intensity improvement	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Technological change in final sources													
Start year policy	0	0	0	0	0	0	0	0	0	0	0	0	0
Speed policy	0	0	0	0	0	0	0	0	0	0	0	0	0
Minimum fraction of this source	0	0	0	0	0	0	0	0	0	0	0	0	0
Max yearly change between sources	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Efficiency rate of substitution													

	Industry												
	Oil	Natural Gas	Wood	;ar Cane Produ	Electricity	LPG	Gasoline	Kerosene	Diesel Oil	Fuel Oil	Gases	Non Energy	Ethanol
Oil		0	0	0	0	0	0	0	0	0	0	0	0
Natural Gas	0		0	0	0	0.02	0	0	0.02	0.02	0	0	0
Wood	0	0		0	0	0	0	0	0	0	0	0	0
Sugar Cane Products	0	0	0		0	0	0	0	0	0	0	0	0
Electricity	0	0	0	0		0.1	0.1	0.1	0.1	0.1	0	0	0
LPG	0	0	0	0	0		0	0	0	0	0	0	0
Gasoline	0	0	0	0	0	0		0	0	0	0	0	0
Kerosene	0	0	0	0	0	0	0		0	0	0	0	0
Diesel Oil	0	0	0	0	0	0	0	0		0	0	0	0
Fuel Oil	0	0	0	0	0	0	0	0	0		0	0	0
Gases	0	0	0	0	0	0	0	0	0	0		0	0
Non Energy	0	0	0	0	0	0	0	0	0	0	0		0
Ethanol	0	0	0	0	0	0	0	0	0	0	0	0	

Figure S.9. Structure of the energy intensities panel of the EEDEC model

As presented in the panel, the case of a trending scenario in the industrial sector is predefined in order to set that no policies of technology or source substitution are implemented (zero value in the year established as starting point for applying the policies), however improvements in energy efficiency are allowed. The ending year is set in 2050, defining the horizon for the analysis in this model. The maximum acceleration in energy efficiency improvement is set in 1% per year, the maximum interchange between energy sources in 5% per year, and a minimum fraction of a source does not exist.

The change of energy source is defined by a greater usage of electricity and natural gas in detriment of oil derivatives without a change in the efficiency. However, policies do not present an effect because the starting year has a zero value. Implementation speed is selected in a qualitative fashion, with values (1-fast, 2-medium, 3-slow). Medium speed implementation presents a linear behavior from the year of application to the final year of policy implementation. Fast speed is predefined by the evolution of a power less than one (coefficient ½), while the slow speed is predefined by a quadratic power (coefficient 2). These coefficients can be modified in the model to get a implementation speed faster or slower depending on which scenarios are built.

1.1.2. Bottom-Up Approach

Bottom-up approach consists in the modelling of each concrete variable and policy, from which the modelling of the variation in energy intensity of a specific sector is implemented. In the case of the model of Ecuador, the transport sector, and explicitly road transport has been disaggregated taking into consideration the vehicle categories light load, medium load, heavy load, buses, and massive rail passenger transport (light rail and metro). Through the number of vehicles, their consumption, technology change policies, among other variables to be explained in the transport module, road transport energy intensities are estimated in the *EI Ground Transport* sub-model.

1.1.3. Bottom-up approach in households

In the case of households, their evolution can be both described by a top-down approach or by a Bottom-up approach. As in the case of the *EI Ground Transport* sub-model, private households transport (*EI Transport Households* sub-model) used a categorization of 4-wheeled gasoline, diesel, hybrid and electric vehicles, and 2-wheeled gasoline and electric vehicles. Using the number of electric and hybrid vehicles that was estimated through the implementation of exogenous policies of technology change, the variation of energy intensity for each type of source used in this sector was estimated.

However, energy intensity in households is not dependent only on the consumption of energy for transport, hence energy intensity in households was split from energy intensity in transport and energy intensity due to other activities.

1.2. Transport Dynamics

1.2.1. Households Transport

To model the variation in the intensities of households' transport, the sub-model *EI Transport Households* was developed using as reference the structure of the MEDEAS model [5]. Considering the bottom-up approach, modelling of this sector takes into account the variation of the energy intensity as function of the percentage share of each vehicle type. For this, the following classification was considered:

- 4-wheeled gasoline, diesel, hybrid, and electric vehicles
- 2-wheeled gasoline and electric vehicles

According to the available information of private vehicle fleet, annual average travel, and energy consumption per kilometer of each technology type (known as Fuel Economy), energy consumption of these vehicles was estimated using the following expression for the case of gasoline vehicles in a year t:

$$Demand_{Gas_t} = \#Vehicles_{4WGas_t} * Average\ Distance_{4W} * Fuel\ Economy_{4WGas} + \#Vehicles_{4WHib_t} * Average\ Distance_{4W} * Fuel\ Economy_{4WHib} + \#Vehicles_{2WGas_t} * Average\ Distance_{2W} * Fuel\ Economy_{2WGas} \quad (A.12)$$

If it is considered that fuel economy for hybrid vehicles is the product of fuel economy of a gasoline vehicle by a saving factor (sr), the consumption would be:

$$\begin{aligned} Demand_{Gas_t} = {} & \#Vehicles_{4WGas_t} * Average\ Distance_{4W} * Fuel\ Economy_{4WGas} \\ & + \#Vehicles_{4WHib_t} * Average\ Distance_{4W} * Fuel\ Economy_{4WGas} * sr_{hib} \\ & + \#Vehicles_{2WGas_t} * Average\ Distance_{2W} * Fuel\ Economy_{2WGas} \end{aligned} \quad (A.13)$$

Once the consumption is obtained, energy intensity of households' transport was determined as the ratio between the estimated energy consumption and the economic demand of households, known as "Private Consumption". Taking into account the case previously described, the intensity would be given by the following expression:

$$EI\ HHT_{Gas_t} = \frac{HH * \%HH_{4wGas} * Av.Dist_{4W} * Eff_{4WGas}}{HHcons} + \frac{HH * \%HH_{4wHyb} * Av.Dist_{4W} * Eff_{4WGas}}{HHcons} + \frac{HH * \%HH_{2wGas} * Av.Dist_{2W} * Eff_{2WGas}}{HHcons} \quad (A.14)$$

If we take in consideration that the number of 4-wheeled and 2-wheeled gasoline vehicles is the product of the total vehicle fleet by the share of each vehicle type with respect to the total, the expression for the intensity is the following:

$$EI\ HHT_{Gas_t} = \frac{HH*\%HH_{4wGas}*Av.Dist_{4W}*Eff_{4WGas}}{HHcons} + \frac{HH*\%HH_{4wHyb}*Av.Dist_{4W}*Eff_{4WGas}}{HHcons} + \frac{HH*\%HH_{2wGas}*Av.Dist_{2w}*Eff_{2WGas}}{HHcons} \quad \text{(A.15)}$$

If the total number of vehicles, average distances, fuel economy, and private consumption remain constant, the variation of the energy intensity (IE) would be described by the expression:

$$\frac{d(IE_{Gas_t})}{dt} = A_1\frac{d(\%HH_{4wGas})}{dt} + A_1\frac{d(\%HH_{4wHyb}*sr_{hyb})}{dt} + A_2\frac{d(\%HH_{2wGas})}{dt} \quad \text{(A.16)}$$

Where:

$$A_1 = \frac{HH*Av.Dist_{4W}*Eff_{4WGas}}{HHcons} \quad \text{(A.17)}$$

$$A_2 = \frac{HH*Av.Dist_{2W}*Eff_{2WGas}}{HHcons} \quad \text{(A.18)}$$

Constant values A_1 and A_2 are obtained from the consumption of energy sources (gasoline in this case) and the economic demand of the last year with available data, 2017 in this case. The change in the percentages of vehicles is determined by the implemented policies, growing in a linear fashion but slowing down as they approach the boundary of 100%.

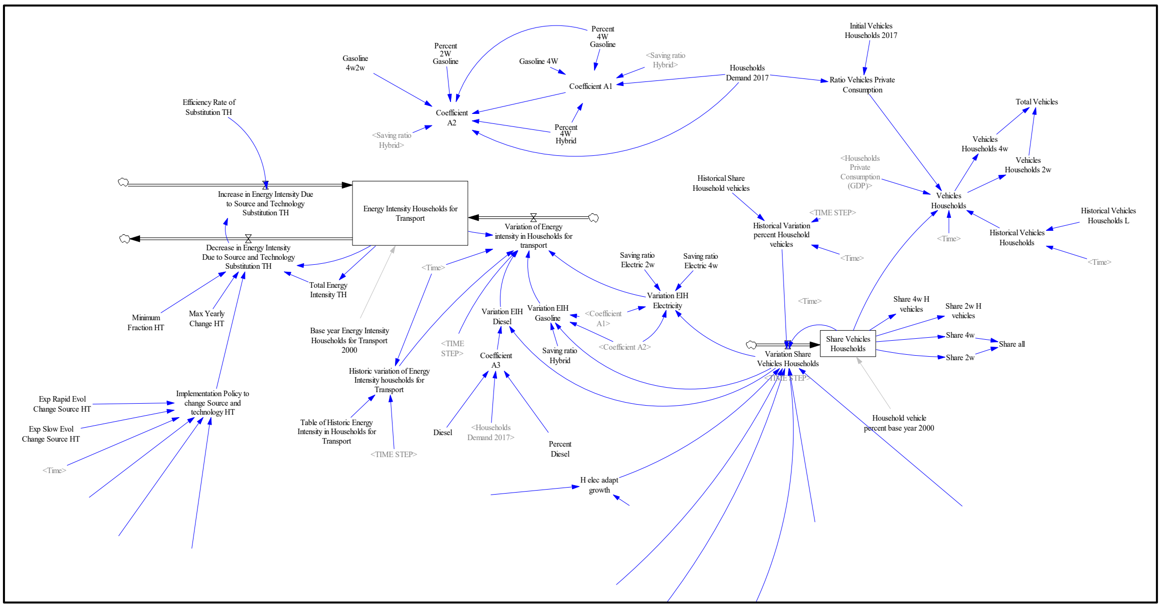

Figure S.10. Modelling structure of the variation of percentages of households' vehicles and energy intensity of households' transport in the EEDEC model

As it can be appreciated in Figure S.8, variation of the intensity is given by the variation in the share of each vehicle type in relation to the total number of household vehicles. The model will take the historical variation until 2017. The variables that describe the change in the share of each vehicle type are highlighted in red in Figure S.11.

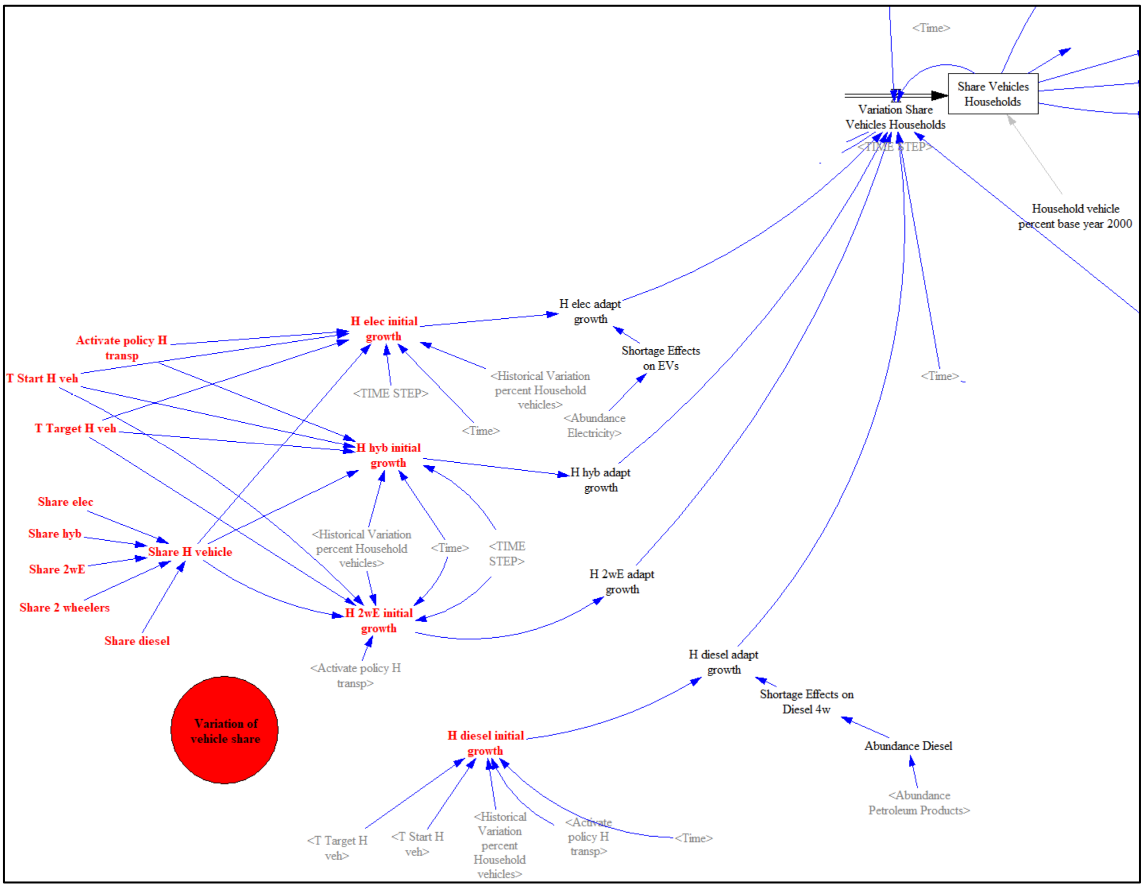

Figure S.11. Modelling structure for policies for the variation of shares in household vehicles in the EEDEC model

As in the case of the dynamics of intensities of the other economic sectors, the variables highlighted in red are exogenously modified in the policies panel shown in Figure S.12.

Transportation			
Activate policy HOUSEHOLDS transport	Dmnl	1	
Activate policy GROUND transport	Dmnl	1	
T ini policy HOUSEHOLDS vehcicles	Year	2020	
T fin policy HOUSEHOLD vehicles	Year	2050	
T ini policy GROUND transp vehicles/Electric train/Electric Trolley	Year	2020	
T fin policy GROUND transp vehicles/Electric train/Electric Trolley	Year	2050	
Households transport policies, desired share of each vehicle in T fin relative to its type (2w or 4w) (alternative 4wheelers policies must add <=1, 2wheeler electric policy must be<=1)			
Policy electric household 4wheeler vehicle Tfin	Dmnl	0.0064	TYPES OF HOUSEHOLD VEHICLES
Policy hybrid household 4w vehicle Tfin	Dmnl	0.0108	4wheeler electric= batery electric vehicles+plug in hybrids
Policy Diesel household vehicle 4w Tfin	Dmnl	0.008	4wheeler hybrid= non plug in hybrids
Policy electric 2wheeler h. Tfin	Dmnl	0.9254	4wheeler gas= natural gas and LPG vehicles
Policy change to 2wheeler h. Tfin	Dmnl	0.3325	2wheeler elec= electric 2 and 2 wheelers

Figure S.12. Structure of the policies panel for modelling the households transport in the EEDEC model

Additionally, the effect of scarcity of the used sources in this sector is considered, causing the increase to present an adaptive behavior and to multiply themselves by a decreasing factor, as shown in Figure S.13.

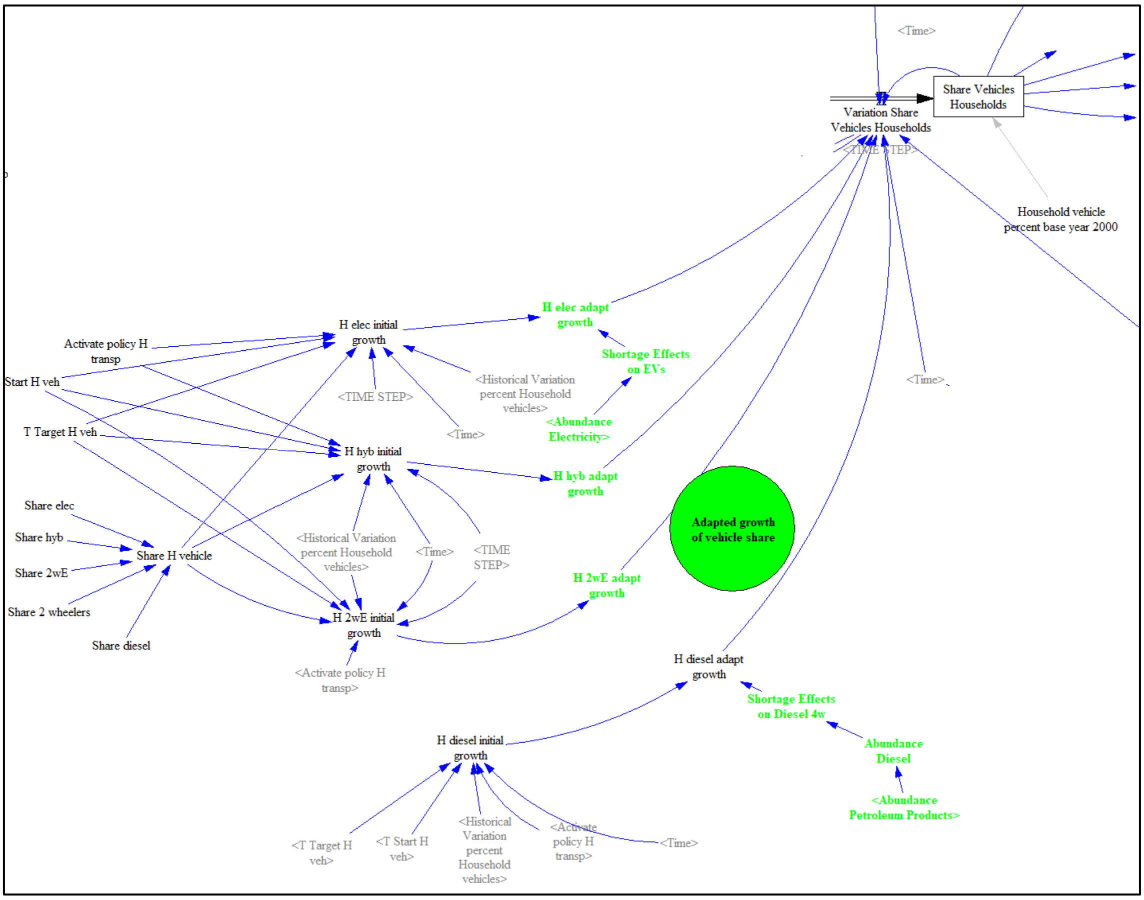

Figure S.13. Modelling structure adapted to energy scarcity of the variation in shares of household vehicles in the EEDEC model

1.2.2. Commercial Ground Transport

In order to model the variation of the intensities in transport sector, the sub-model *EI Ground Transport* was developed using as reference the structure of the sub-model Inland Transport in the MEDEAS model [5]. Taking into account the bottom-up approach, modelling in this sector considers, for ground transport, the variation of energy intensity as a function of the percentage share of each vehicle type. For this end, the following classification was developed:

- Light load vehicles (LV), by Gasoline, Diesel, Hybrid and Electric
- Heavy load vehicles (HV), by Gasoline, Natural Gas, Diesel and Hybrid
- Vans, by Gasoline, Diesel, Hybrid and Electric
- Buses, by Gasoline, Natural Gas, Diesel, Hybrid and Electric
- Electric Mass Transport (Light Rail and Metro)

Using the available data of commercial vehicle fleet, annual average distances, and energy consumption by kilometer (Fuel Economy) of each technology, the energy consumption of these vehicles was estimated. In the case of gasoline cars for a given year t, and taking as reference the model for household transport, the expression would be described by:

$$Demand = \#Vehicles_{LVGas_t} * Average\ \ Distance_{LV} * Fuel\ Economy_{LVGas} + \#Vehicles_{LVHib_t} * RAverage\ \ Distance_{LV} * Fuel\ Economy_{LVGas} * sr_{LVhib} + \#Vehicels_{HVGas_t} * Average\ \ Distance_{HV} * Fuel\ Economy_{HVGas} + \#Veicles_{HVGas_t} * Average\ \ Distance_{HV} * Fuel\ Economy_{HVGas} * sr_{HVhib} + \#Vehicles_{BusGas_t} * Average\ \ Distance_{Bus} * Fuel\ Economy_{BusGas} \quad (A.19)$$

To calculate the intensity, the economic activity of the transport sector or sectorial GVA (*X*) is considered, obtaining the following expression:

$$EI\ Transp_{Gas_t} = \frac{\#Vehicles_{LVGas_t} * Average\ Distance_{LV} * Fuel\ Economy_{LVGas}}{X_t} + \frac{\#Vehicles_{LVHib_t} * Average\ Distance_{LV} * Fuel\ Economy_{LVGas} * sr_{LVhib}}{X_t} + \frac{\#Vehicles_{HVGas_t} * Average\ Distance_{HV} * Fuel\ Economy_{HVGas}}{X_t} + \frac{\#Veicles_{HVGas_t} * Average\ Distance_{HV} * Fuel\ Economy_{HVGas} * sr_{HVhib}}{X_t} + \frac{\#Vehicles_{BusGas_t} * RAverage\ Distance_{Bus} * Fuel\ Economy_{BusGas}}{X_t} \quad (A.20)$$

Following the same procedure as in the case of household transport, the number of vehicles is expressed as a function of the total number and the percentage share, assuming that average distances and fuel economy have a constant value, the variation in the intensity is characterized by the following expression:

$$\frac{d(EI\ Transp_{Gas_t})}{dt} = NX_{LV(t_0)} * cm_{LVGas} * \frac{d(\%Vehicles_{LVGas_t})}{dt} + NX_{LV(t_0)} * cm_{LVGas} * \frac{d(\%Vehicles_{LVhib_t} * sr_{LVhib})}{dt} + NX_{HV(t_0)} * cm_{HVGas} * \frac{d(\%Vehicles_{HVGas_t})}{dt} + NX_{HV(t_0)} * cm_{LVGas} * \frac{d(\%Vehicles_{HVhib_t} * sr_{HVhib})}{dt} + NX_{Bus(t_0)} * cm_{BusGas} * \frac{d(\%Vehicles_{BusGas_t})}{dt} \quad (A.21)$$

Where:

$$NX_{LV(t_0)} = \frac{\#Vehicles\ Tot_{LV}}{X_{t_0}} \quad (A.22)$$

$$NX_{HV(t_0)} = \frac{\#Vehicles\ Tot_{HV}}{X_{t_0}} \quad (A.23)$$

$$NX_{Bus(t_0)} = \frac{\#Vehicless\ Tot_{Bus}}{X_{t_0}} \quad (A.24)$$

These expressions are determined using as base data available for the most recent year, 2017 in this case.

$$cm_{LVGas} = Average\ Distance_{LV} * Fuel\ Economy_{LVGas} \quad (A.25)$$

$$cm_{HVGas} = Average\ Distance_{HV} * Fuel\ Economy_{HVGas} \quad (A.26)$$

$$cm_{BusGas} = Average\ Distance_{Bus} * Fuel\ Economy_{BusGas} \quad (A.27)$$

As in the case of households' transport, the increase in the percentage of vehicles is determined by the policies implemented and grow linearly slowing down as they approach the 100%

boundary. In Figure S. 14 the variation in intensity is presented, which is defined by the variation in the share of each type of vehicle with respect to the total number of commercial vehicles.

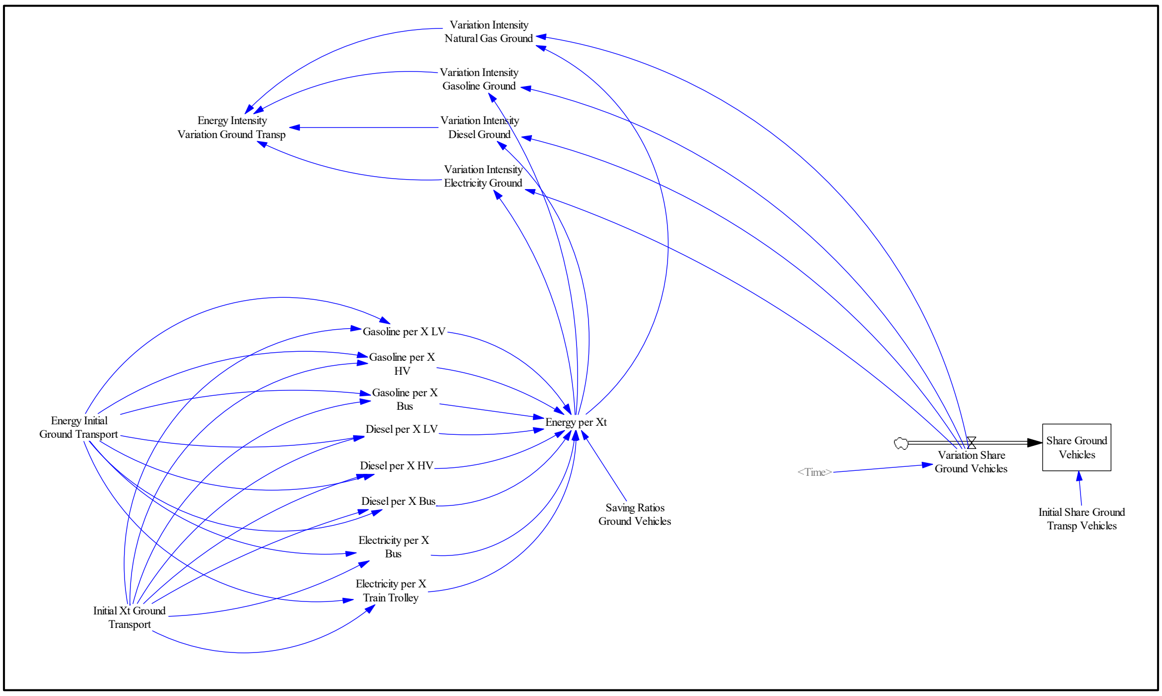

Figure S.14. Modelling structure of the variation in the share of commercial vehicles and energy intensity of the transport sector in the EEDEC model

The model will take the historic variation up to 2017. The variables that describe the change in the share of each vehicle type relative to the total are highlighted in red color in Figure S.15 and are exogenously adjusted in a policies panel similar to the one used for Households transport that is depicted in Figure S.16.

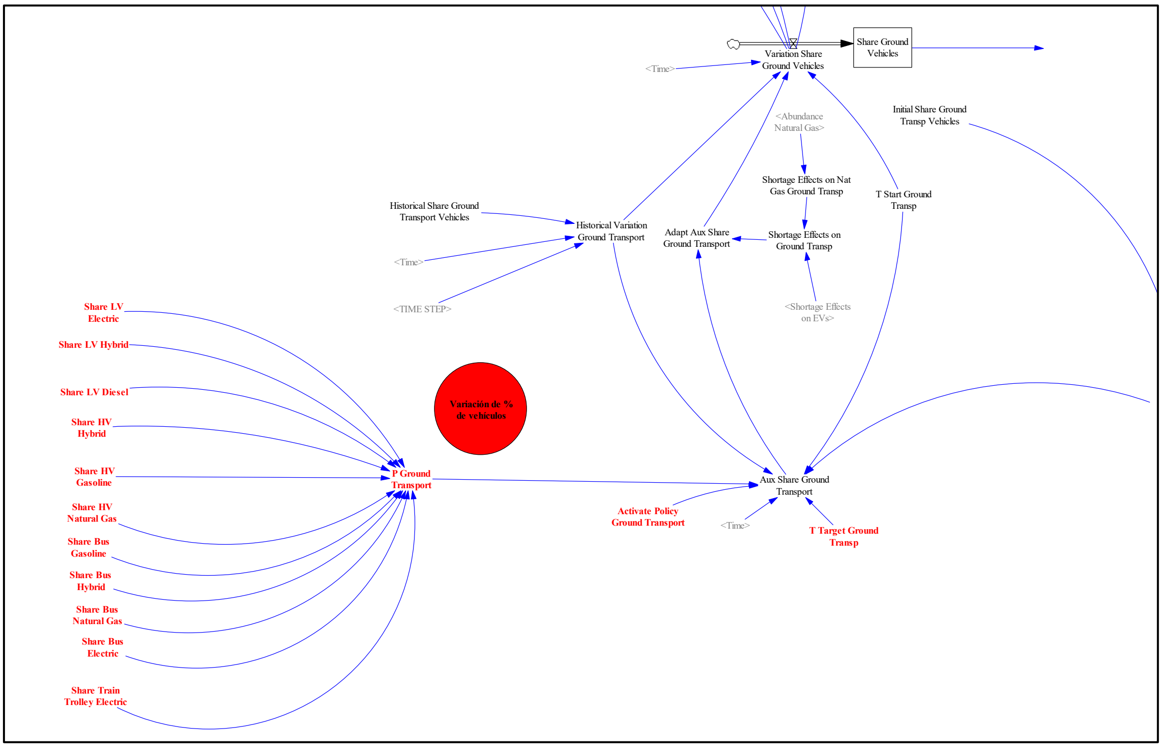

Figure S.15. Estructura del modelamiento de políticas para variación de porcentajes de vehículos comerciales en el modelo EEDEC

As in the case of households' transport, it is taken into account the effects of the scarcity of the sources used in this sector that causes the increase to be multiplied by a decreasing factor.

Ground transport sector policies, desired share of each alternative vehicle in T fin relative to its type (HV, LV, bus, train)			(alternative policies must add <=1 for each type of vehicle)
Policy hybrid HV Tfin	Dmnl	0.2	TYPES OF INLAND TRANSPORT SECTOR VEHICLES
Policy gasoline HV Tfin	Dmnl	0.2	HV= heavy vehicles
Policy Natural Gas HV Tfin	Dmnl	0.3	
Policy electric LV Tfin	Dmnl	0.15	LV= light cargo vehicles
Policy hybrid LV Tfin	Dmnl	0.15	bus= buses and coaches (urban and non urban)
Policy Diesel LV Tfin	Dmnl	0.2	
Policy electric bus Tfin	Dmnl	0.1	
Policy hybrid bus Tfin	Dmnl	0.2	
Policy gasoline bus Tfin	Dmnl	0.2	
Policy Natural Gas Bus Tfin	Dmnl	0.15	
Policy Electric train/Trolley Tfin	Dmnl	1	

Figure S.16. Structure of the policies panel for modelling the commercial transport in the EEDEC model

1.3. Dynamics of Electricity Generation

To model electricity generation, two sub-models were developed: one for fossil-fueled generation and another one for generation with renewable sources. Unlike the structure used in the Energy Balance, which makes a distinction between public power plants and autoproducers (electricity producers that generate for their own consumption, and mainly belong to the industrial, commercial and residential sectors) , the presented model works with a single category of electricity generation that integrates the two described previously. The structure used for both sub-models uses as reference the MEDEAS model.

1.3.1. Electricity Generation with Fossil Fuels

To model electricity generation with fossil fuels three level variables have been considered: the capacity required to generate with these sources, the planned capacity as a function of the system requirements, and the installed capacity available once the planned one has been built. The fossil fuels taken into account are: Crude oil, Natural Gas, LPG, Gasoline, Diesel Oil, and Fuel Oil..

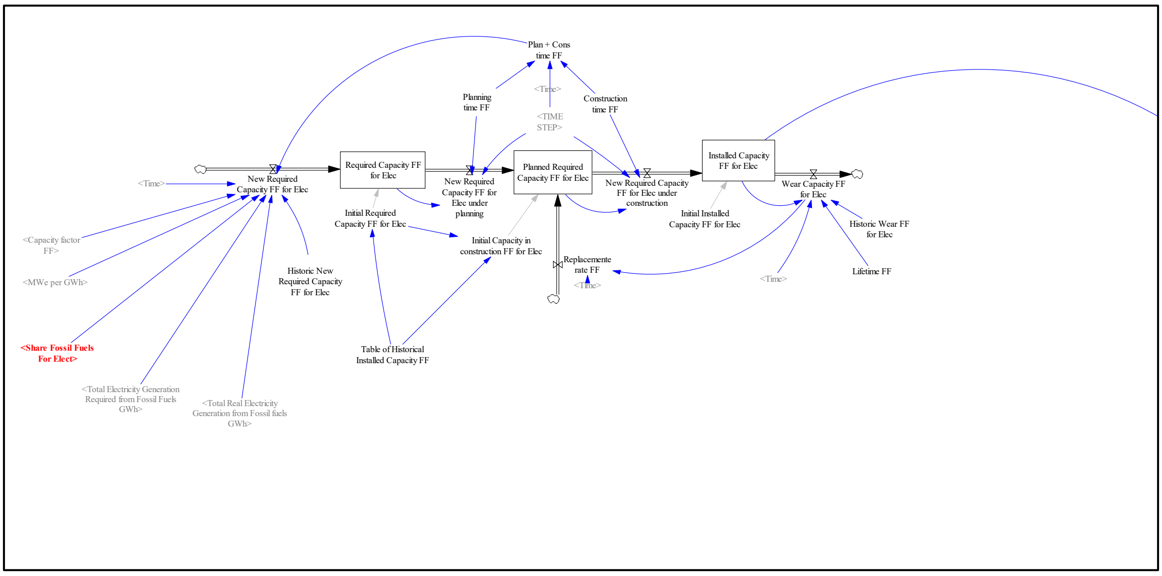

Figure S.17. Modelling structure of the dynamics of electricity generation with fossil fuels in the EEDEC model

As shown in Figure S.17, the new capacity required will be defined by the historical capacity required up until 2017, the share of fossil fuels in the generation mix (Share Fossil Fuels), the required generation by these sources, and the real generated energy; these variables are highlighted in red. The required planned capacity is leveled at the same time by the required capacity in the planning stage and the one that once planned proceed to the construction phase. Finally, the installed capacity is leveled by the capacity in the construction stage and the one that reaches its useful life. In this sense, the planning and construction times of each technology type define the rate at which the capacity is planned and built. These variables are established exogenously.

The share of fossil sources in the electricity generation mix is at the same time another level variable, which is defined by policies that increase or decrease the share of the fuels. The variables corresponding to policies are highlighted in red in Figure S.18. On the other hand, the variation of this share is conditioned by the scarcity of fossil sources used for electricity generation, which are highlighted in green and follow the same logic used in the energy intensity and transport sub-models.

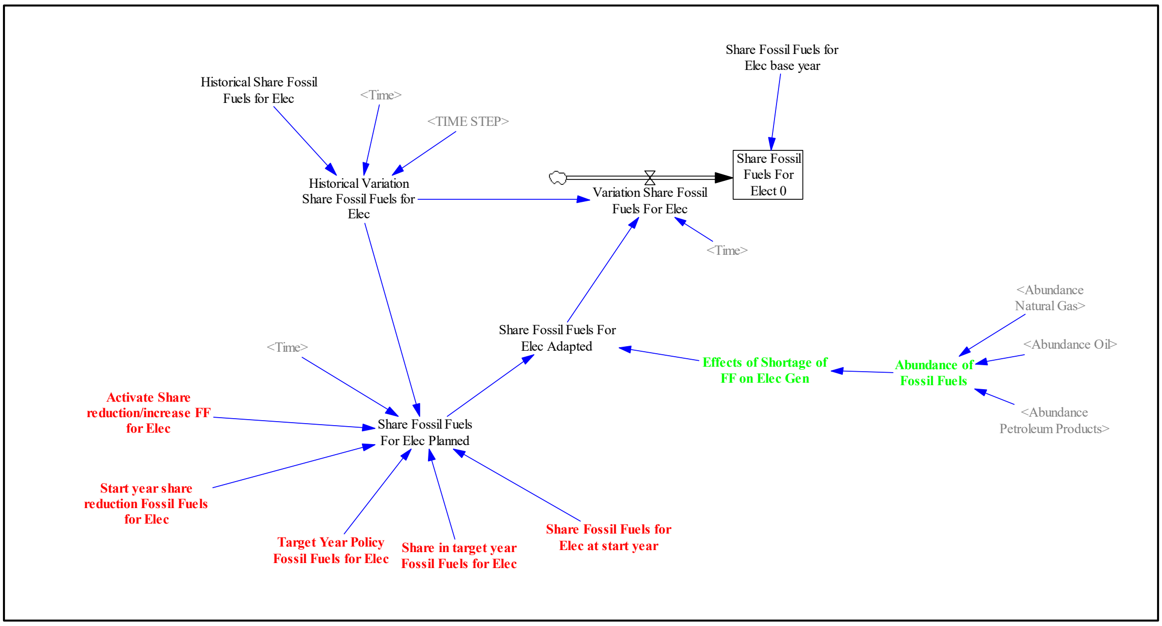

Figure S.18. Modelling structure of the dynamics of the share of fossil sources in electricity generation in the EEDEC model

1.3.2. Electricity generation with renewable sources

To model the electricity generation with renewable sources (*RES Capacity sub-model*), following the structure of the fossil fuels sub-model, three level variables have been considered: required capacity to generate with these sources, planned capacity as a function of the system requirements, and the installed capacity, once the planned one has been built. The renewable sources taken into consideration are: Hydro, Wind, Solar Photovoltaic, Geothermal, Biomass and Biogas.

As shown in Figure S.19, the required new capacity will be defined by the historical capacity required up until 2027, the remaining renewable resource, and the policies implemented to boost the growth of the installed capacity for each renewable source that are highlighted in red and that are exogenously adjusted in the same way than in the sub-models described for other sectors.

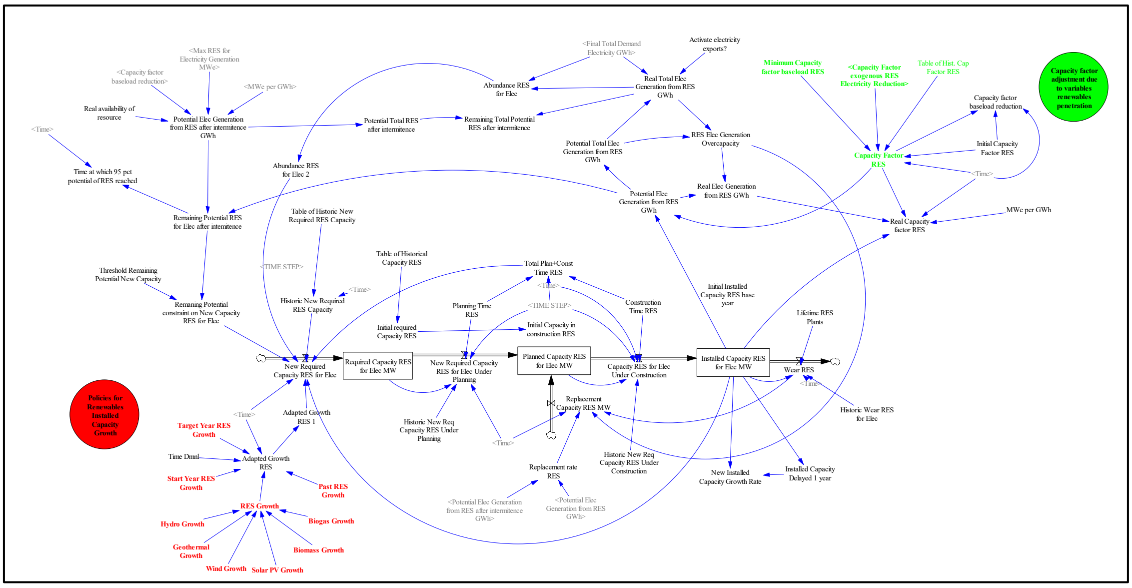

Figure S.19. Modelling structure of the dynamics of electricity generation with renewable sources in the EEDEC model

Figure S.19 at the same time depicts the similar structure in both electricity generation sub-models, with the exception of the level variable corresponding to the planned capacity.

In the modelling of electricity generation with renewables, it has been considered the intermittent behavior that is usually seen with this type of generation and the adjustment of the capacity factors that are necessary due to this intermittency. The variables that modify this factor are depicted in green in Figure S.19. The reduction of the capacity factor (<Capacity Factor exogenous RES Electricity Reduction>) is related at the same time with the share of the renewable generation with variable resources with respect to the total generation. These variables allow estimating the infrastructure overcapacity of the generation with renewables. Figure S 20 shows the dynamics of the variable renewable sources share as a function of the total generation [5].

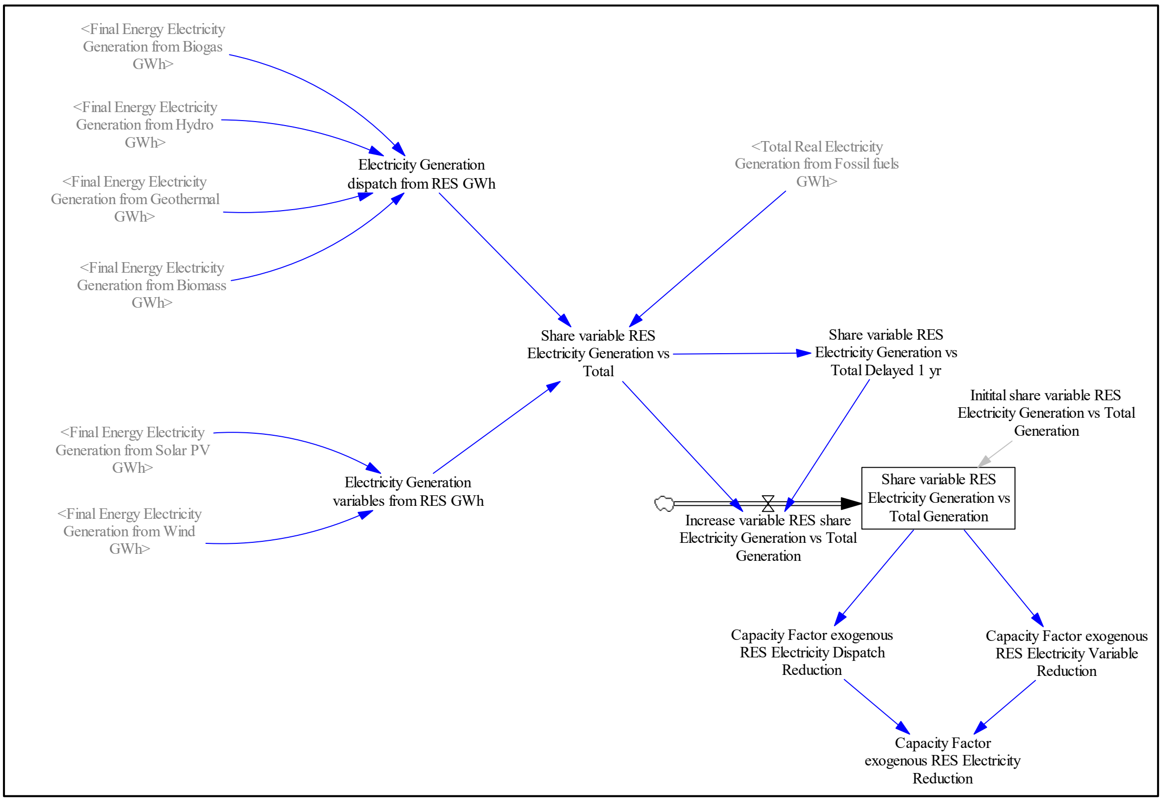

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Figure S.20. Modelling structure of the overcapacity of electricity generation with renewable sources in the EEDEC model

1.3.3. Electricity Losses

Electricity transmission and distribution losses have been modelled considering the available historical data (up to 2017) and the national policies designed to reduce these losses, which variables are highlighted in red in Figure S.21.

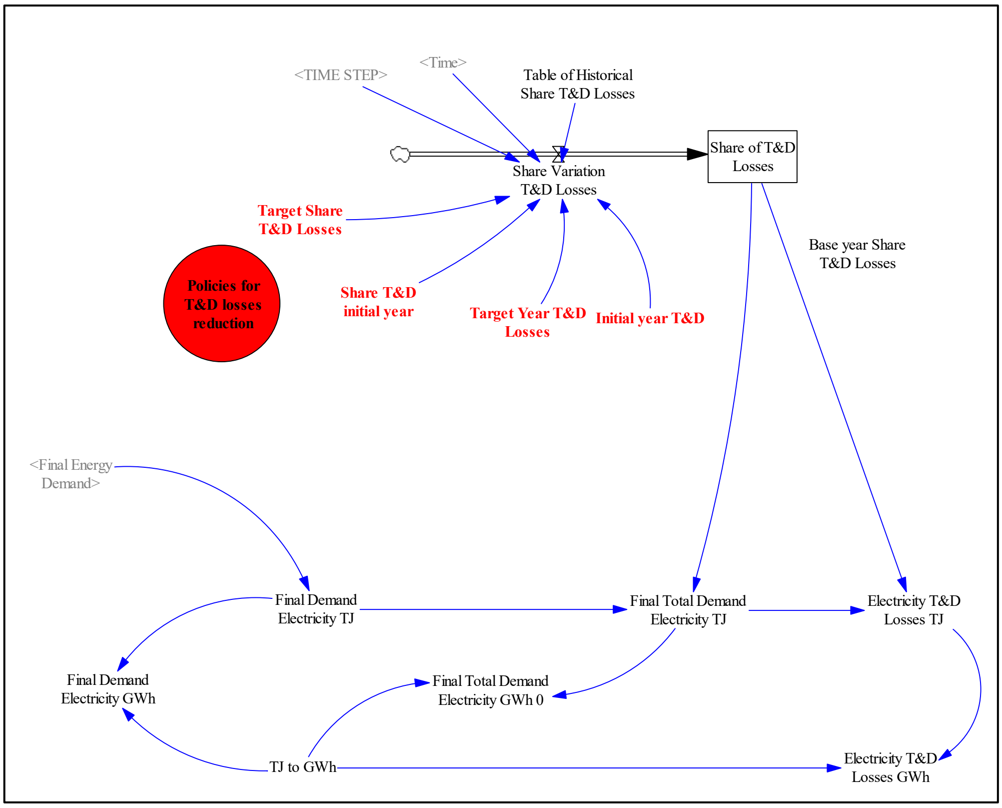


Figure S.21. Modelling structure of electricity transmission and distribution losses in the EEDEC model

1.3.4. Renewable Resources for electricity generation

To modelling the new capacity requirements for electricity generation with renewable sources remnant resources were considered, which at the same time depend on the maximum usable potential in both economic and technical terms. Figure S.22 describes the structure of the *RES Potential* sub-model, in which the maximum usable potentials are taken into account from the available bibliography. In the cases of geothermal, biomass, and biogas sources, conversion factors are considered, depending on the technology used, for their transformation to electricity. In the case of solar energy, its maximum potential has been defined using as variables the available surface for this type of plants and the installable capacity per surface unit.

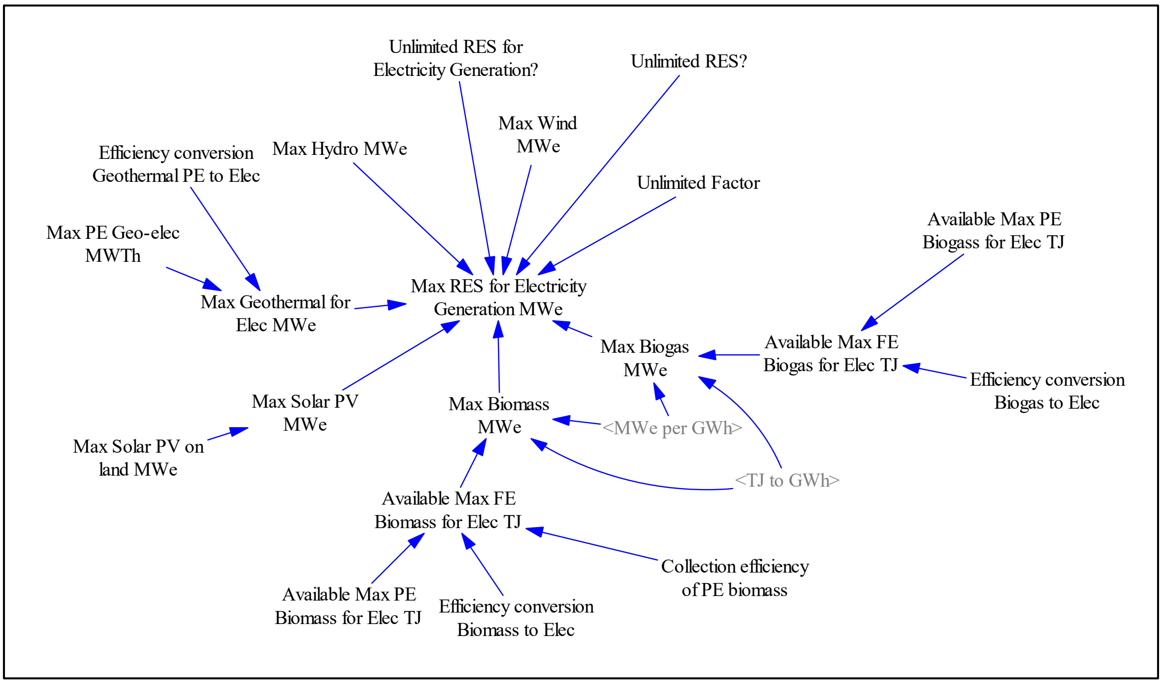


Figure S.22. Modelling structure of the maximum potential of renewable resources for electricity generation in the EEDEC model

1.4. Dynamics of the production of crude oil, oil products, natural gas and ethanol

1.4.1. Production of oil products and gas

To model the production of oil products and gas, refineries and liquefied petroleum gas centers have been taken into account. Relative to refinery products, the model included an aggregation of Fuel Oil and Residual Oil contained in the National Energy Balance under the single category Fuel Oil. In this sense, secondary sources and vectors corresponding to refinery products are: LPG, Gasolines, Kerosene-Jet Fuel, Diesel Oil, Fuel Oil, Non-energetics, and Gases.

Figure S.23 describes the structure of the developed sub-model, inside which the demand of the described sources (considering the demand of the economic sectors and fuels demand for electricity generation) and the processing capacities of the refineries and gas centers constitute the variables that determine the national derivative production. These two last variables at the same time are determined by the increase in capacity and their decommissioning after fulfilling their usable life.

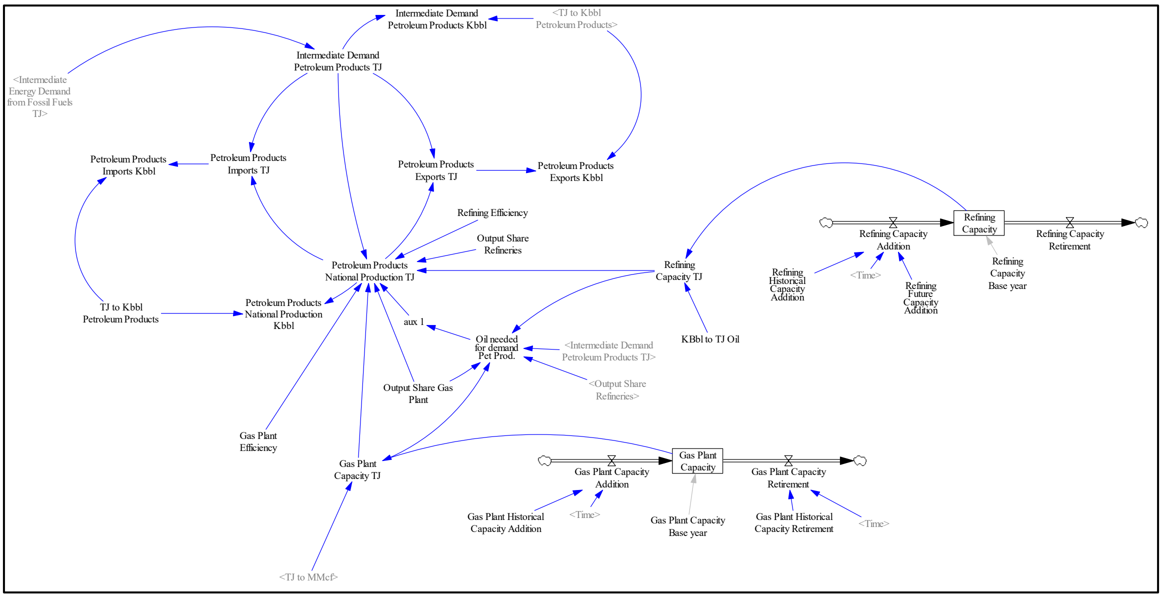


Figure S.23. Modelling structure of the production of oil products and gas in the EEDEC model

If the demand of oil products is lower than the maximum production capacity of refineries and gas centers, these facilities will operate to fulfill these requirements. In the case that demand surpasses the maximum capacity, the transformation facilities will produce at their limit and the deficit will be covered with imports.

1.4.2. Production of Ethanol

Production of ethanol, source that is used in Ecuador by the ground transport sector in a mix with gasolines, has a dynamic like the one of the refineries and gas centers where the refining capacity and demand are the variables that regulate how much ethanol needs to be produced.

In Figure S.24, the modelling structure of the distilleries is depicted, showing that the capacity of the plants depends on the rate at which the mentioned capacity is being aggregated. Historical information will be used up until 2017, and then the capacity will be added in function of the demand and the criterion of increasing the capacity or not doing it (variable *Increase Capacity?*). As in the case of the previous instances, production will be determined as the minimum between ethanol demand and maximum production capacity. In the case that demand is larger than capacity, the deficit will be covered with imports. It is worth mentioning that the raw materials fed to the distilleries are molasses and sugarcane juice, and for now these liquids are not considered a restrictive variable.

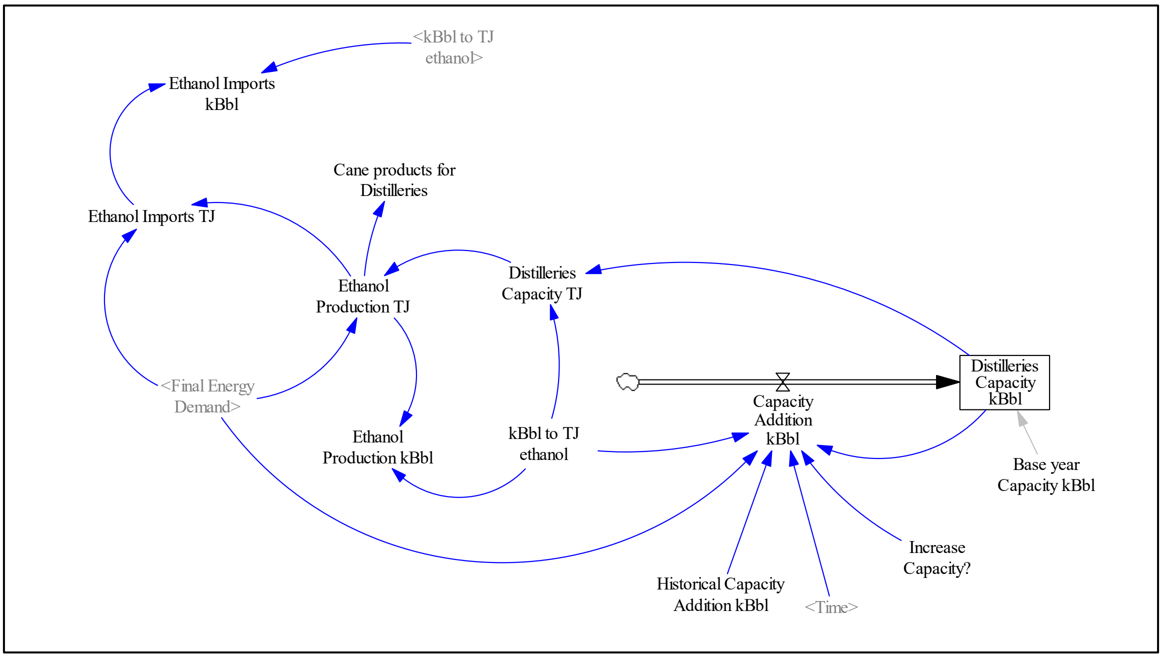


Figure S.24. Modelling structure of the production of ethanol in the EEDEC model

1.4.3. Oil and Natural Gas Availability

The availability of oil and natural gas in EEDEC model is subject to two constraints:

- Stock: which is the available resource in the ground, in this case in million barrels
- Flow: which is the extraction rate of the resource, in this case in million barrels per year

Stock availability of a resource is generally measured in terms of ultimately recoverable resources (URR), or remaining URR (RURR) if it corresponds to a particular year. The latter is defined as the difference between the URR and cumulative extraction in time t.

$$RUUR_t = URR - Cumulative\ Extraction_t \quad \text{(A.28)}$$

To estimate the future availability of oil, Hubbert based models from Espinoza et al [6]. were considered. This study developed future oil extraction projections curves under a national (top-down) and blocks (bottom-up) approach, considering two cases for URR: 1) 7,800 MBbl, and 2) 10,700 MBbl. In the study, the median of the extraction values for the best-fitted models was obtained. These curves (Figure S.25) represent maximum extraction profiles under geological constrains (no demand or investment constraints are considered) as a function of time.

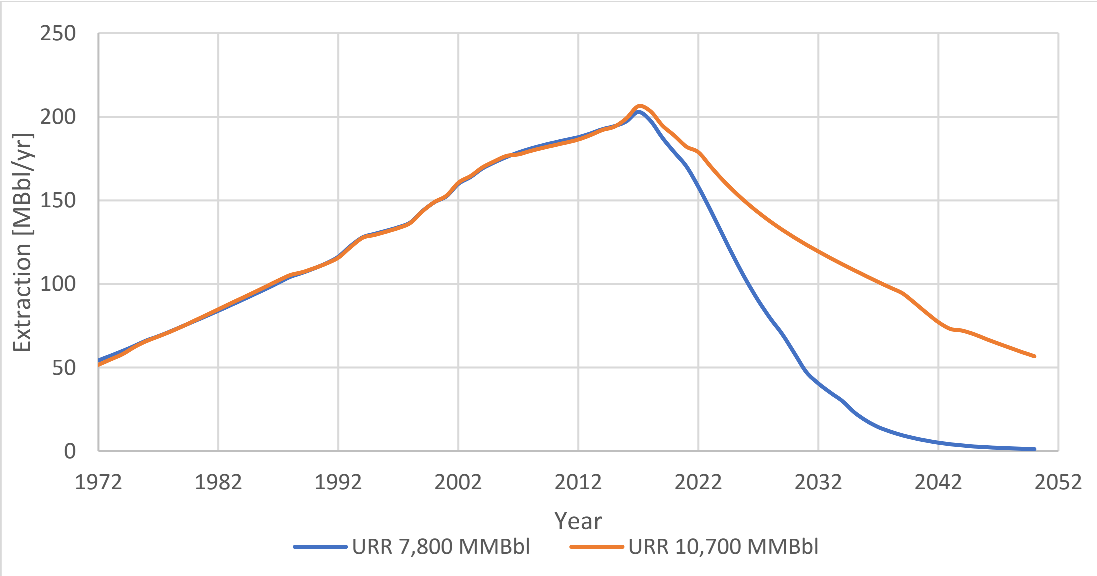


Figure S.25: Median values of extraction profiles for URR 7,800 MBbl and 10,700 MBbl from Espinoza et al.

To incorporate them as inputs in the model, oil depletion curves were converted, since demand is endogenously modelled. It has been assumed that, while the maximum extraction rate given by the depletion curve is not reached, oil extraction matches the demand. Real extraction will therefore be the minimum between the domestic requirements and exports, and the maximum extraction rate (see Figure S.26 a)). To do this, the depletion curves were transformed into maximum extraction curves as a function of remaining resources. In these curves, extraction is only restricted by the maximum extraction level, with the provision that remaining resources are large. However, with cumulative extraction, there is a level of remaining resources when physical limits start to show, and maximum extraction rates are gradually reduced. To this extent, the model uses a stock of resources (or RURR) and it studies how this stock is depleted depending on extraction, which is determined by domestic requirements, exports, and maximum extraction (Figure S.26 b)).

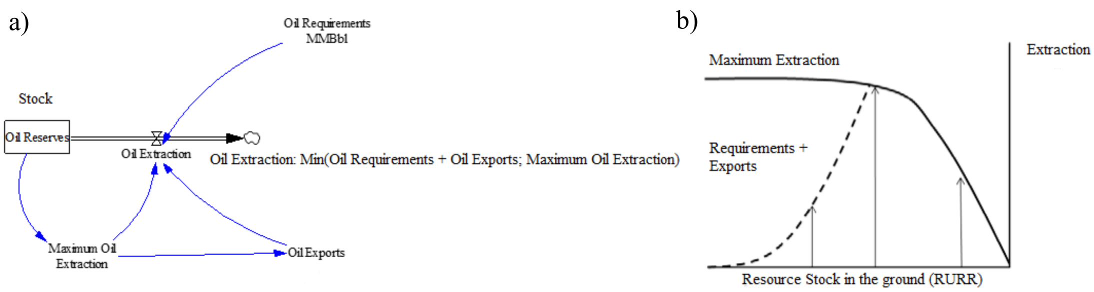
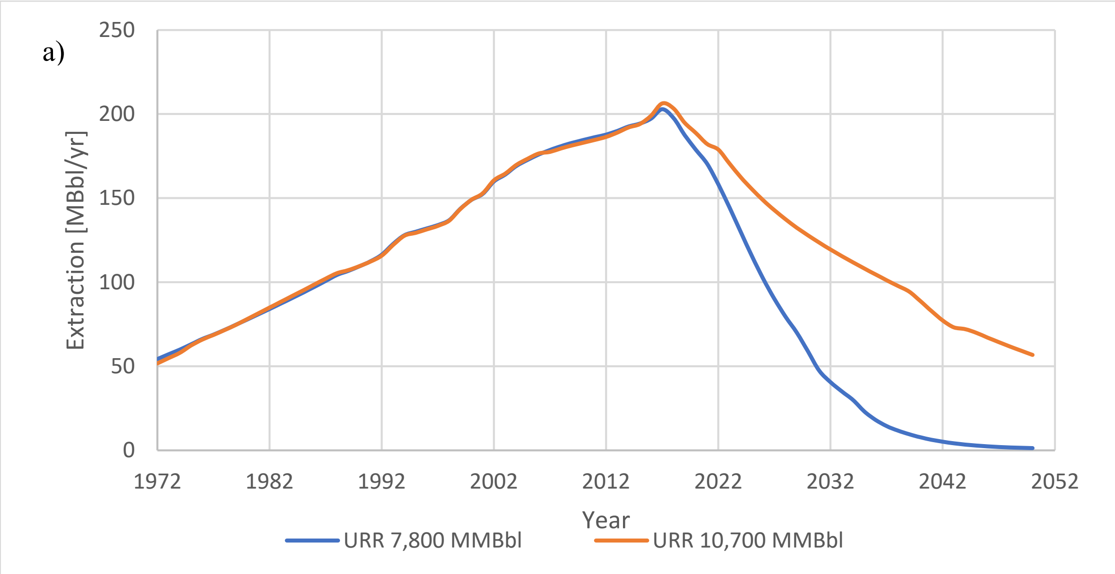


Figure S.26: Integration of depletion curves in EEDEC model. (a) System Dynamics model. (b) A curve of maximum extraction (solid) compared with the requirements plus exports (dashed) (adapted from Mediavilla et. al) [7].

Figure S.27 a) shows the depletion curves as a function of time from Espinoza et al, and Figure S.27 b) depicts the associated curves of maximum extraction as a function of the RURR.



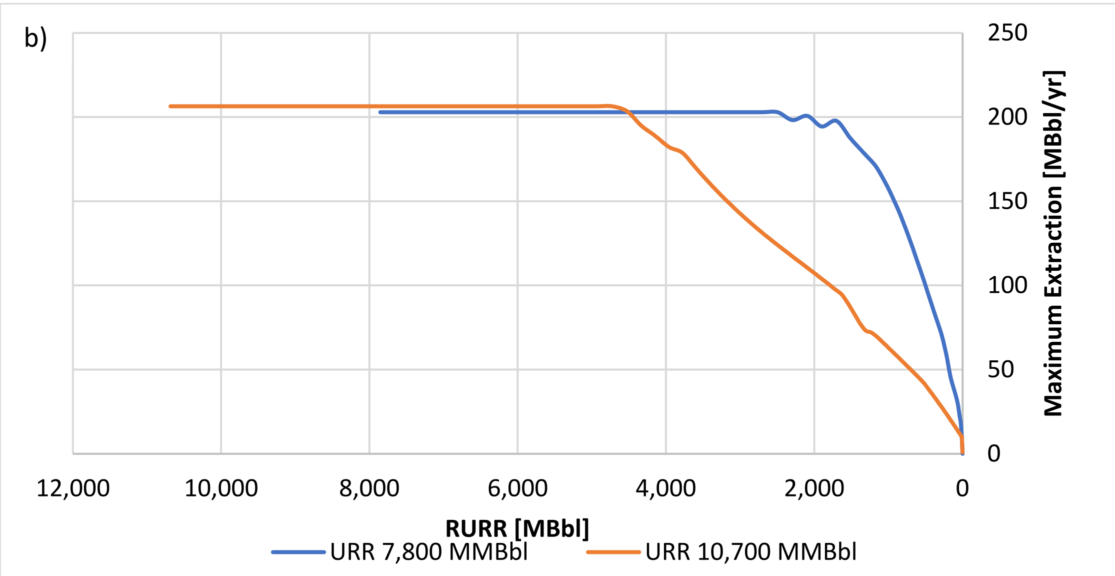


Figure S.27: Oil availability: (a) depletion curves as a function of time from the original reference; (b) curves of maximum extraction in function of the RURR as implemented in the model. The y-axis represents the maximum achievable extraction rate (MBbl/year) in function of the RURR (MBbl). The extreme left point represents the URR. As extraction increases and the RURR fall below the point where the maximum extraction can be achieved, the extraction is forced to decline following the estimations from Espinoza et al. [6]

Regarding Natural gas, a Hubbert based model was developed taking as reference the methodology used in Espinoza et al. Information related to reserves and extraction was taken from the 2018 annual report of Ecuador's hydrocarbon potential [8], and historic extraction was taken from the 2017 National Energy Balance[9]. Four models were tested: single cycle symmetric, single cycle asymmetric, multi cycle symmetric, and multi cycle asymmetric. The model with the lowest variance coefficient was multi cycle asymmetric model with 9%. URR estimated from [8] was 655.414 Million standard cubic feet [MSCF]. Following the same approach as with oil, a curve of maximum extraction as a function of the RURR was developed as seen in Figure S.28 b).

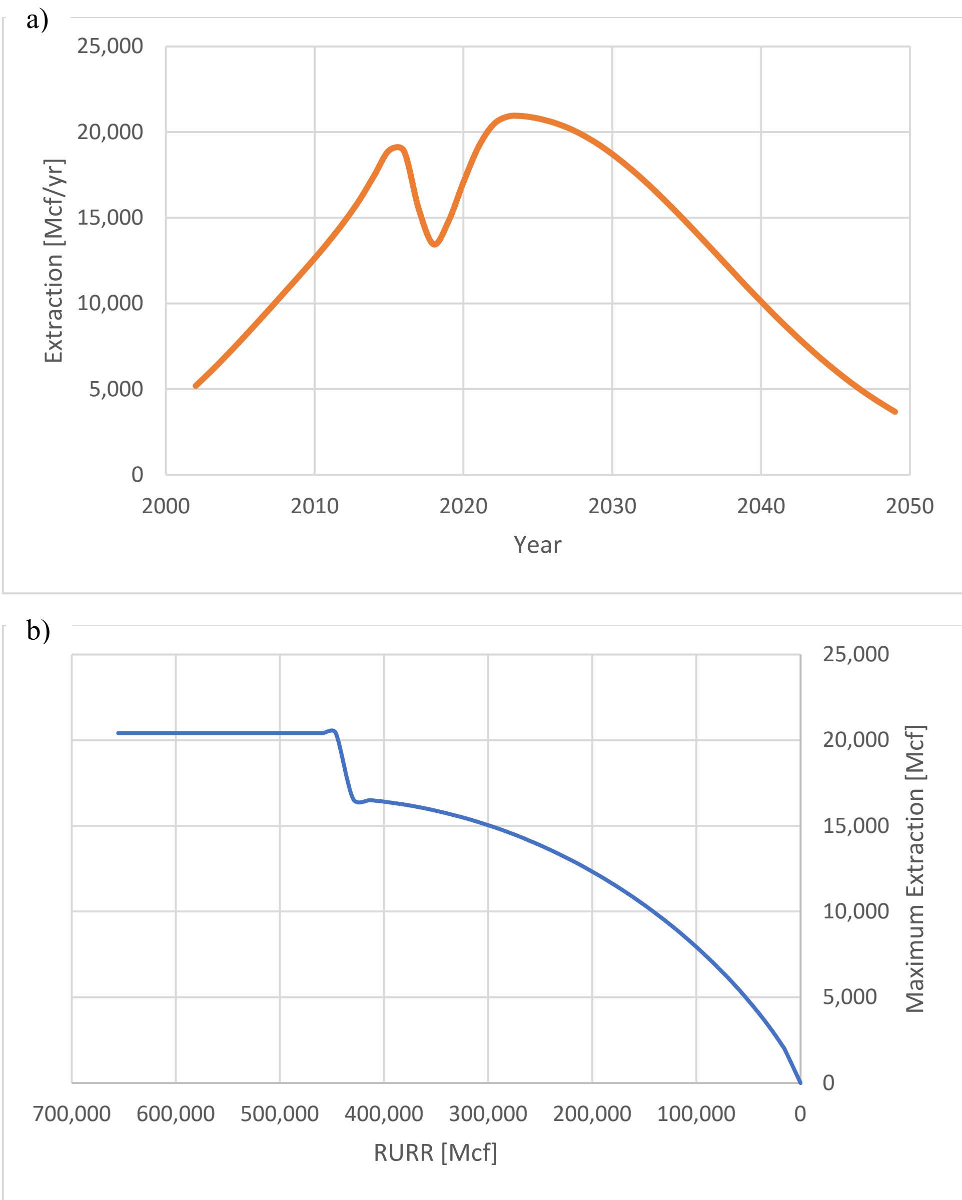


Figure S.28: Natural Gas Availability: (a) depletion curve as a function of time; (b) curve of maximum extraction in function of the RURR as implemented in the model. The y-axis represents the maximum achievable extraction rate (Mcf/year) in function of the RURR (Mcf). The extreme left point represents its URR. As extraction increases and the RURR falls below the point where the maximum extraction can be achieved, the extraction is forced to decline.

1.4.4. Oil Extraction

Oil extraction, as described in Figure S.29, depends on the requirements corresponding to oil processed in refineries and oil used in electricity generation and self-consumption, export policies and maximum extraction which at the same time depends on the remnant reserves or RURR.

Maximum extraction is defined at the same time by the maximum extraction curves for each URR. In this sense, the level variable Reserves will have as value at the base year of simulation the difference between the accumulated oil extraction in that year and the URR, which can have two values depending on the scenario.

Regarding exports, three policy cases have been proposed: maximum exports, exports to cover internal demand, and reduced exports. Finally, oil extraction will be equal to the minimum value between the maximum extraction and the sum of the internal requirements and exports. Concerning oil imports, these will depend on international supply based on MEDEAS [5] and the share of Ecuador of worldwide oil demand.

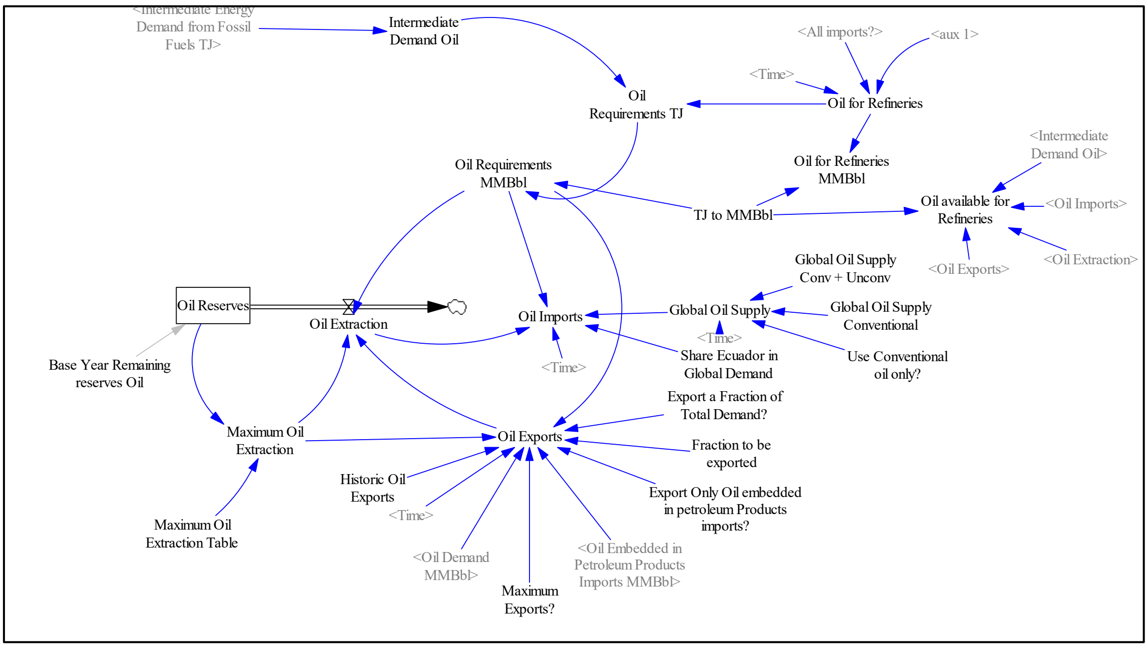


Figure S.29. Modelling structure of crude oil extraction in the EEDEC model

1.4.5. Nonassociated Natural Gas Extraction

In the case of natural gas extraction, as shown in Figure S.30, the same methodology than in the case of oil extraction was used, but without taking in consideration possible natural gas exports due to the fact that the URR of this resource is too small.

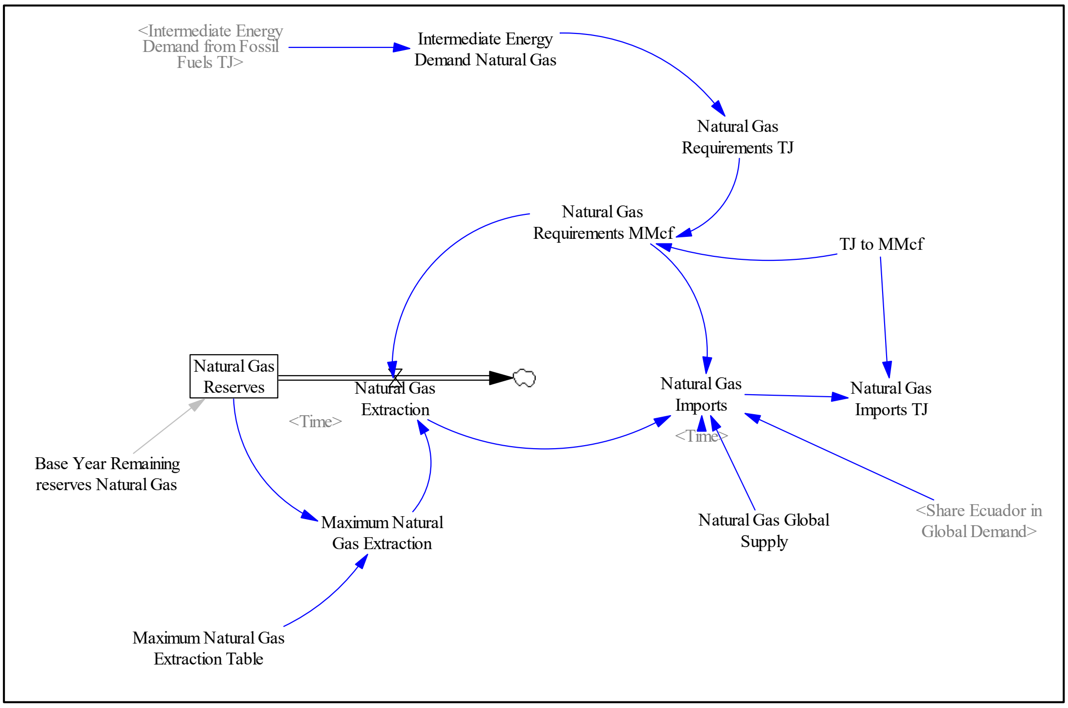


Figure S.30. Modelling structure of nonassociated natural gas extraction in the EEDEC model

1.4.6. Associated Natural Gas Extraction

Extraction of Associated Natural Gas will be directly linked to the extraction of crude oil given that it is a sub-product of this process. In Figure S.31 the structure of the dynamics of associated natural gas extraction is depicted, considering oil extraction and remnant oil reserves in the base year. It is important to reiterate that no information of associated natural gas reserves is available, and the extraction values are uncertain; due to this, a ratio between historical production of crude oil and associated gas was calculated and used.

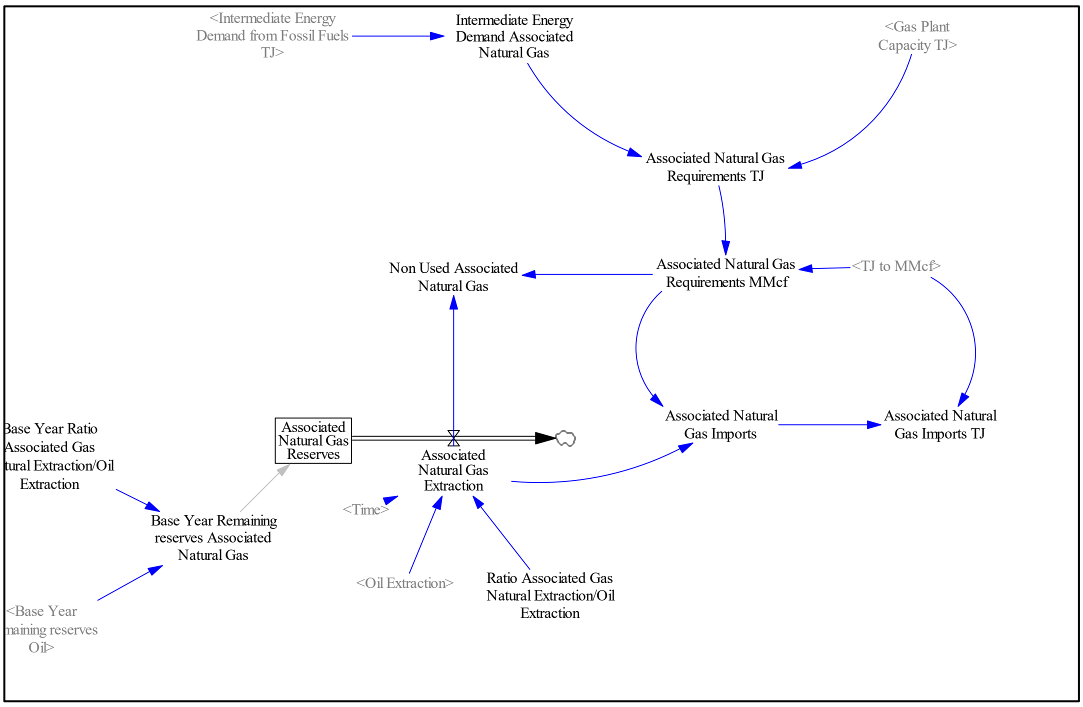


Figure S.31. Modelling structure of associated natural gas extraction in the EEDEC model

1.5. Dynamics of energy demand

1.5.1. Final demand

Final energy demand (*FEDik*) per sector and final source in EEDEC model is calculated as the product of GDP per sector *Xi* and sectoral energy intensities for each final energy source *EIk*. An indicator that has been applied for measuring energy efficiency. Even though this indicator has both an engineering (based on thermodynamics) and macroeconomic concept [10], the latter has been generally used for estimating future energy demand in several models [11–16].

$$FED_{ik} = EI_{ik} * X_i \quad \text{(A.29)}$$

Sectorial GDP starts from the economic model used in *Escenarios de prospectiva energética para Ecuador a 2050* [16]. A scenario of economic growth with an annual average rate of 2.73% has been considered, taken into account the forecasts of OLADE [17]. This expected GDP growth is subjected to energy availability as it was described in section 1.1.

In the case of electricity, it is important mentioning that losses are taken in consideration, which alongside consumption constitutes final demand.

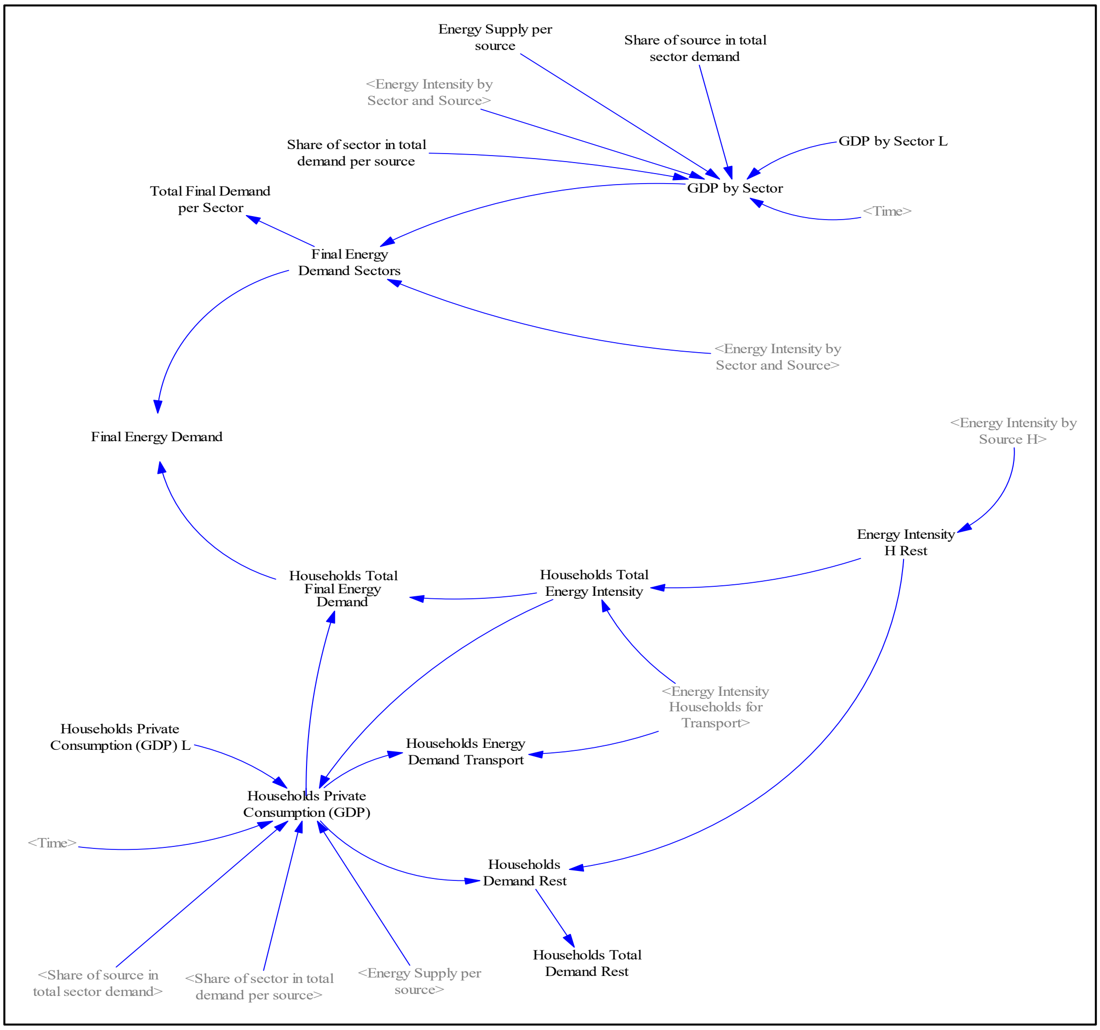


Figure S.32. Modelling structure of Energy demand in the EEDEC model

1.5.2. Intermediate Demand

Intermediate demand corresponds to the sum of final demand and energy demand for electricity generation, specifically fossil sources. This variable plays a fundamental role to determine the amount of oil derivatives to be produced, and the amount of natural gas and crude to be extracted.

1.5.3. Abundance of sources

To estimate sources abundance, a ratio between supply and demand of each energy source is determined (in the case that only a final demand or intermediate demand exists, depending on the source). Figure S.33 characterize the modeling of the abundance of oil derivative products, in which are included the primary energy demand corresponding to the aforementioned sources (and which is equal to the intermediate demand), and the primary energy supply which is equal to the addition of domestic production and imports. Abundance value will range between zero and one, with the second value corresponding to equilibrium between supply and demand.

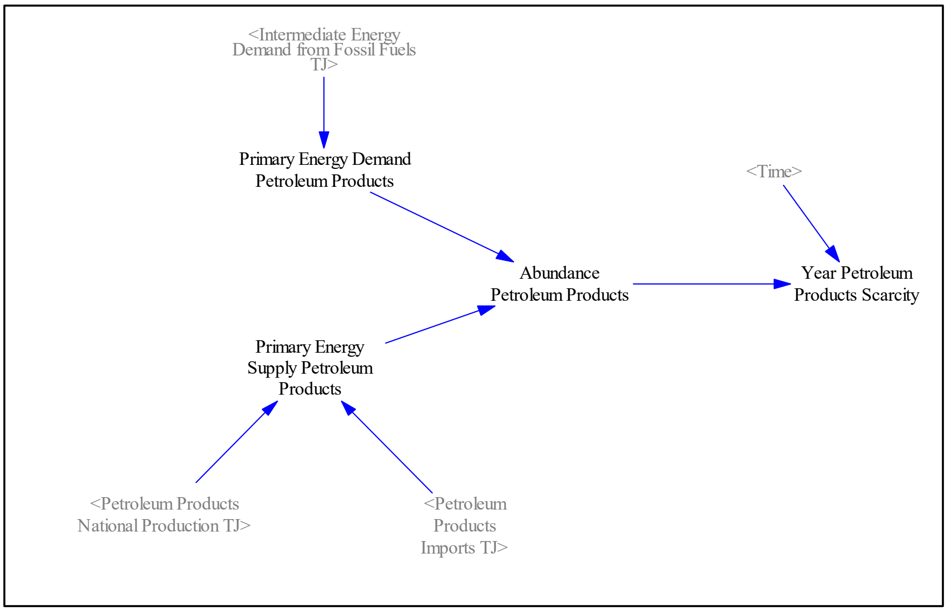


Figure S.33. Modelling structure of abundance of energy sources in the EEDEC model

According to the current model structure, in principle it is posed that no restrictions exist around imports of all secondary energy sources, and primary sources crude oil and natural gas. However, for alternative scenarios imports policies will be considered around the availability of oil and natural gas, which will be determined by worldwide supply of oil and natural gas obtained in the global MEDEAS model.

1.5.4. Emissions

To quantify emissions, the following activities have been considered: crude oil and natural gas extraction, electricity generation, and final demand of the economic sectors (including households). CO_2, CH_4 and N_2O emissions are estimated using IPCC Guidelines and emission factors [18], and reported in CO_{2eq}. Figure S.34 depicts the model structure to calculate emissions from final energy demand.

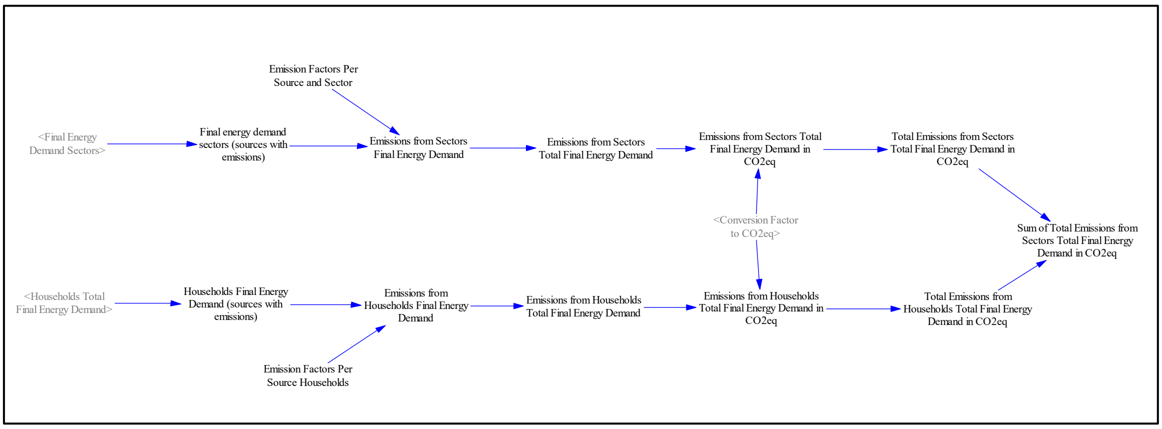


Figure S.34. Modelling structure of emissions in the EEDEC model

1.5.5. Indicators

Indicators used to assess energy transition were taken from the IEA [19], and are divided in energy supply: (1) Final energy carbon intensity, and (2) Power Carbon intensity; and energy demand: (3) Electricity share in final demand. Indicators for oil developed are: (1) Relative Oil exports: is the amount of crude oil exported; (2) Net Oil exports: which is the difference between relative crude oil exports and crude oil imbedded in petroleum products imports, and (3) Share of Oil refined for domestic demand, that is the ratio between crude oil imbedded in the quantity of petroleum products produced that are used to satisfy domestic demand, and total crude oil refined. Figure S.35 a) and b) depict the modeling structure for indicators.

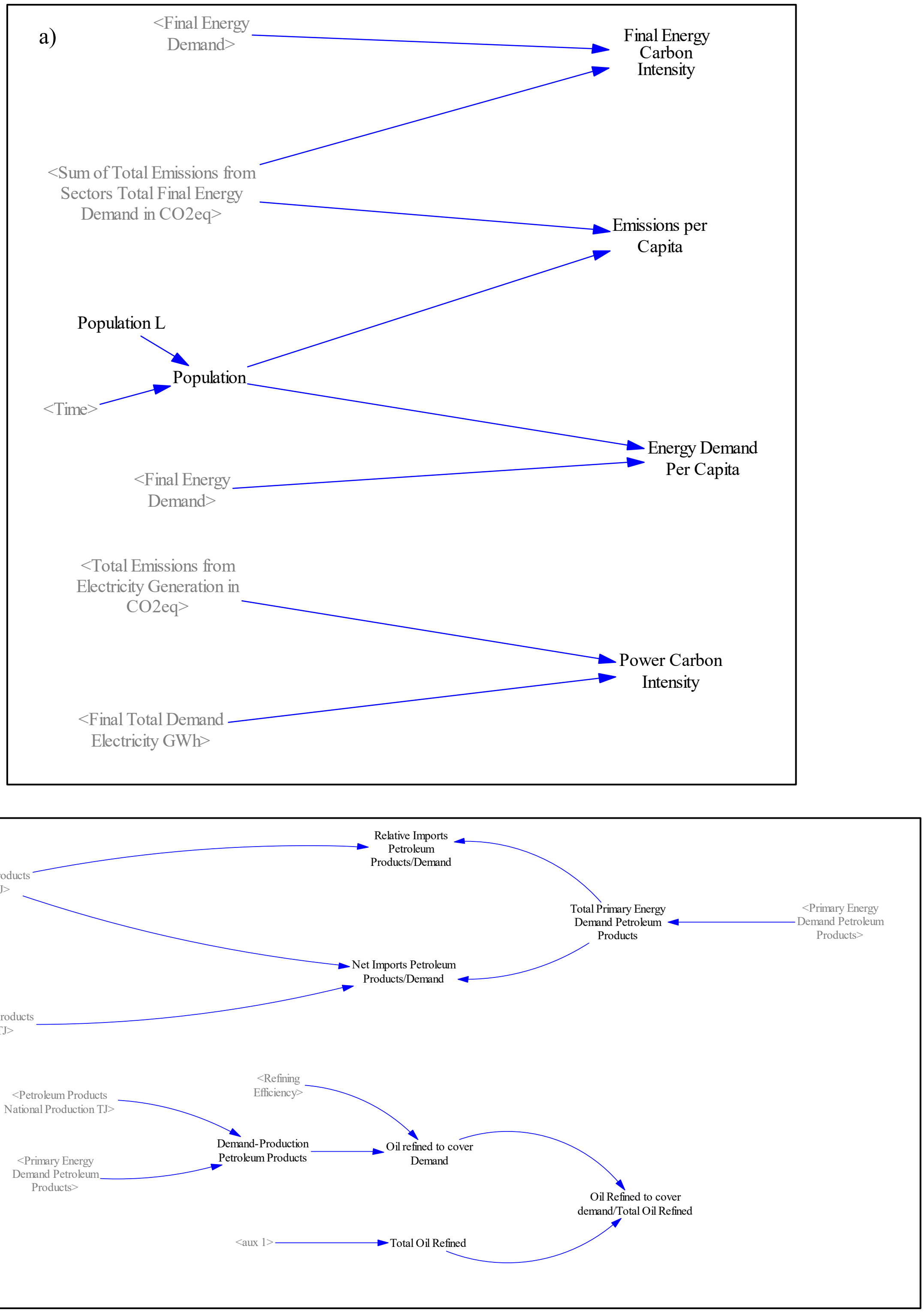


Figure S.35. Modelling structure of a) energy transition indicators y b) oil and derivatives indicators in the model EEDEC

1.5.6. Trade balance

To model Fossil fuels economic trade balance, oil and natural gas prices were taken from World Energy Model documentation [20] and its three scenarios: Stated policies, Sustainable development, and Delayed recovery. Given that the model provides data prices each five years (see Table S.4.), and up to 2040, a reconstruction of times series was performed to obtain yearly prices and project them up to 2050 as seen in Table S.5.

Table S.4. Oil and Natural gas prices from World Energy model [20]

Year	Oil (USD/Bbl)			Natural Gas (USD/MBTU)		
	Scenario			Scenario		
	Stated Policies	Sustainable Development	Delayed Recovery	Stated Policies	Sustainable Development	Delayed Recovery
2025	71	57	59	3.5	2.1	3.1
2030	76	-	-	3.5	-	-
2035	81	-	-	3.8	-	-
2040	85	53	72	4.2	2.0	3.7

Table S.5. Oil and Natural gas prices time series, developed based on World Energy model [20]

Year	Oil (USD/Bbl)			Natural Gas (USD/MBTU)		
	Scenario			Scenario		
	Stated Policies	Sustainable Development	Delayed Recovery	Stated Policies	Sustainable Development	Delayed Recovery
2020	35.00	35.00	35.00	2.00	2	2.00
2021	42.20	39.40	39.80	2.30	2.3	2.30
2022	49.40	43.80	44.60	2.60	2.6	2.60
2023	56.60	48.20	49.40	2.90	2.9	2.90
2024	63.80	52.60	54.20	3.20	3.2	3.20
2025	71.00	57.00	59.00	3.50	2.1	3.20
2026	72.00	56.73	59.87	3.50	2.09	3.23
2027	73.00	56.47	60.73	3.50	2.09	3.27
2028	74.00	56.20	61.60	3.50	2.08	3.30
2029	75.00	55.93	62.47	3.50	2.07	3.33
2030	76.00	55.67	63.33	3.50	2.07	3.37
2031	77.00	55.40	64.20	3.56	2.06	3.40
2032	78.00	55.13	65.07	3.62	2.05	3.43

2033	79.00	54.87	65.93	3.68	2.05	3.47
2034	80.00	54.60	66.80	3.74	2.04	3.50
2035	81.00	54.33	67.67	3.80	2.03	3.53
2036	81.80	54.07	68.53	3.88	2.03	3.57
2037	82.60	53.80	69.40	3.96	2.02	3.60
2038	83.40	53.53	70.27	4.04	2.01	3.63
2039	84.20	53.27	71.13	4.12	2.01	3.67
2040	85.00	53.00	72.00	4.20	2.00	3.70
2041	85.80	52.73	72.87	4.28	1.99	3.73
2042	86.60	52.47	73.73	4.36	1.99	3.77
2043	87.40	52.20	74.60	4.44	1.98	3.80
2044	88.20	51.93	75.47	4.52	1.97	3.83
2045	89.00	51.67	76.33	4.60	1.97	3.87
2046	89.80	51.40	77.20	4.68	1.96	3.90
2047	90.60	51.13	78.07	4.76	1.95	3.93
2048	91.40	50.87	78.93	4.84	1.95	3.97
2049	92.20	50.60	79.80	4.92	1.94	4.00
2050	93.00	50.33	80.67	5.00	1.93	4.03

To determine the average price of Ecuadorian Crude Oil and imported oil products, information from the National Energy Balance, and the Central Bank was retrieved [21,22]. As a first approximation, a linear relationship between crude oil prices and the respective oil products was assumed. Crude oil, exports, and oil products imports and exports in physical and monetary units in Tables A.6 and A.7, respectively, were used to calculate the average price for gasoline, diesel and LPG. Fuel Oil price was calculated as well (Table S.8).

Table S.6. Oil trade Balance for Ecuador (MMbbl)

Year	Crude Oil Exports MBbls	Oil products imports MBbl		
		Gasoline	Diesel	LPG
2012	124	14	17	9
2013	134	16	21	10
2014	149	20	25	11
2015	146	19.5	23.7	10.8
2016	139	16	18.1	9.9
2017	135	16.4	17.9	10.4
2018	130	17.6	20.3	11.2
2019	140	20.4	21.4	12.1

Table S.7. Oil trade Balance for Ecuador (MMUSD)

Year	Crude Oil Exports MUSD	Oil products imports MMUSD		
		Gasoline	Diesel	LPG
2012	12,711	1,663	1,974	771
2013	13,412	2,048	2,318	644
2014	13,016	2,108	2,746	658
2015	5,539	1,161	1,791	397
2016	4,441	970	1,018	314
2017	6,190	1,185	1,233	470
2018	7,853	1,554	1,839	532
2019	7,731	1,632	1,798	385

Table S.8. Estimated Crude Oil and Oil product prices (USD/Bbl)

Year	Crude Oil Price USD/Bbl	Oil product price USD/Bbl imports			Oil product price USD/Bbl exports
		Gasoline	Diesel	LPG	Fuel Oil
2012	102.8	116.6	116.0	85.5	99.6
2013	99.9	127.7	111.2	67.3	92.3
2014	87.5	105.8	110.0	61.3	77.0
2015	37.8	59.6	75.6	36.7	38.2
2016	32.0	60.6	56.4	31.7	30.0
2017	45.7	72.4	69.1	45.0	44.7
2018	60.6	88.2	90.1	47.6	55.3
2019	55.3	80.1	84.02	31.8	49.9

Crude Oil Price obtained was plotted as an independent variable versus Gasoline, Diesel, LPG, and Fuel Oil prices, respectively. A linear regression was performed, obtaining equations with a correlation coefficient higher than 0.9, as seen in the results depicted in Figures A.36-A.39.

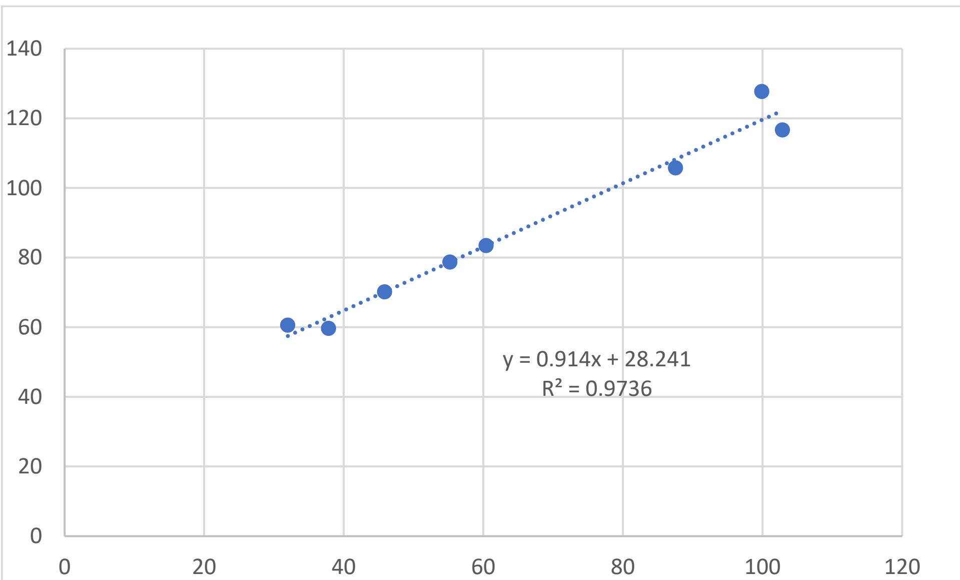


Figure S.36. Linear regression Crude oil price vs Gasoline Price

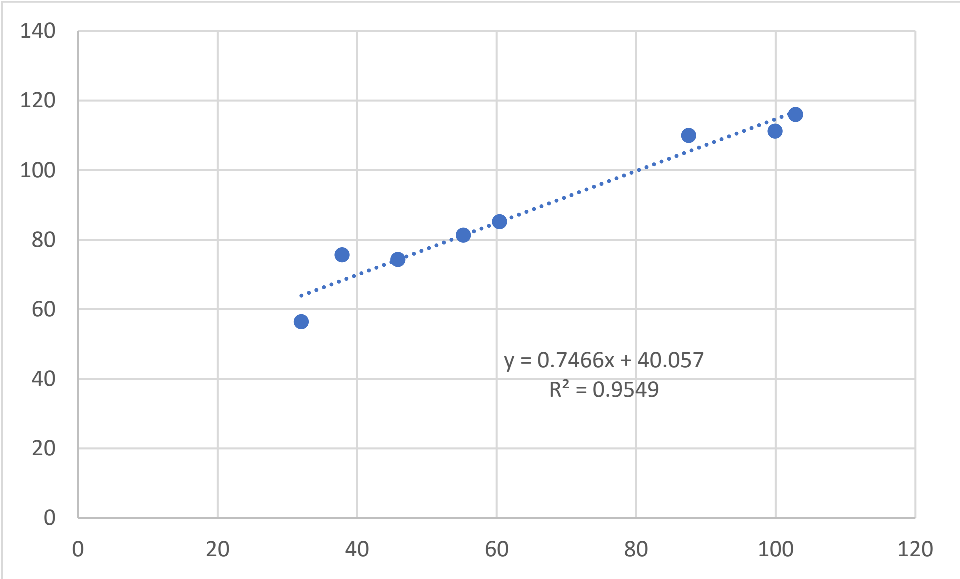


Figure S.37. Linear regression Crude oil price vs Diesel Price

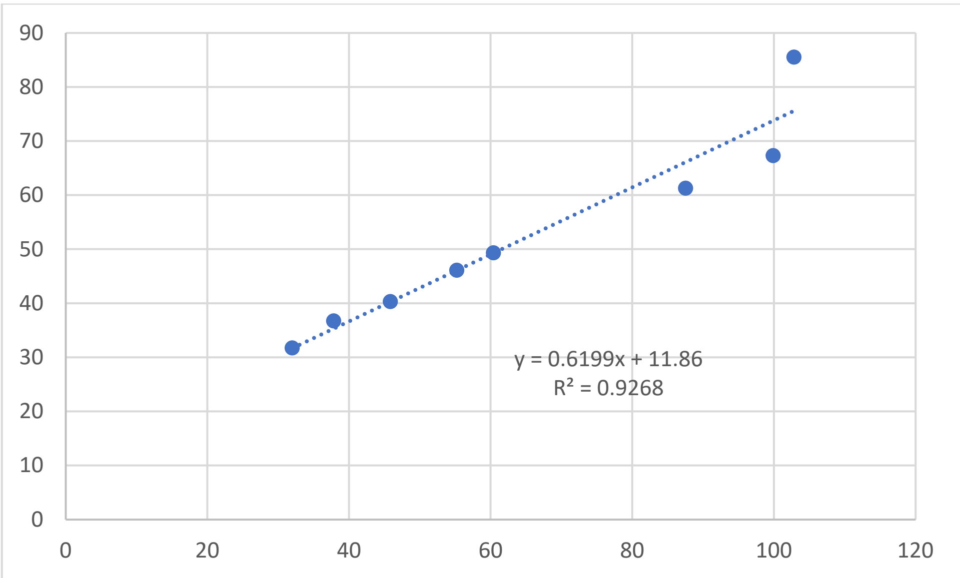


Figure S.38. Linear regression Crude oil price vs LPG Price

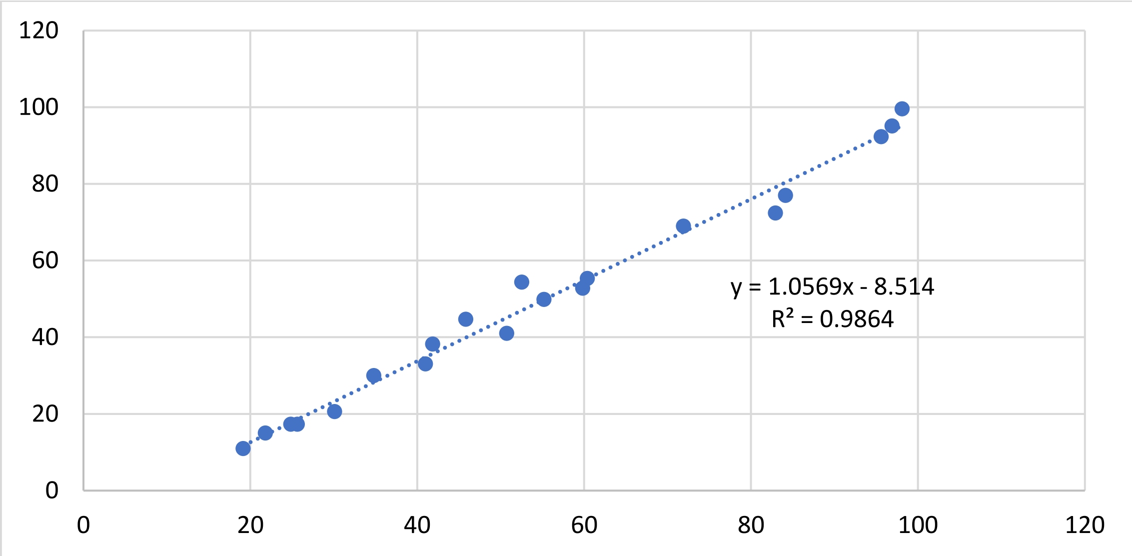


Figure S.39. Linear regression Crude oil price vs Fuel Oil Price

Fossil fuels imports and exports are quantified in physical units. The product of this variables and fuels prices allows the estimation of the economic trade balance as depicted in Figure S.40.

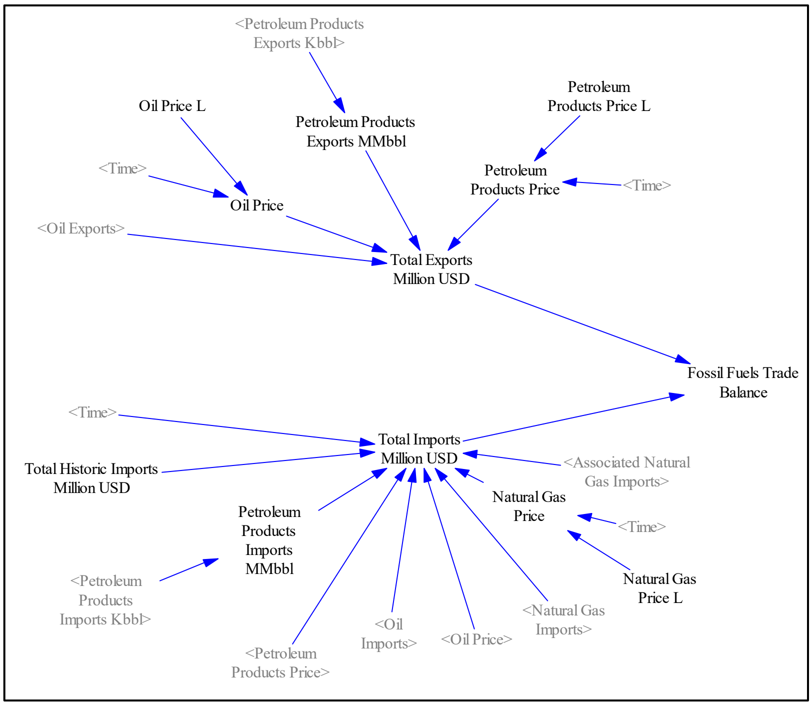


Figure S.40. Modelling structure of the economic trade balance of fossil fuels in the EEDEC model

2. Scenario Design

Scenarios are an exploratory and detailed description of conceivable, viable and coherent future situation of a system, which can occur from the sequence of interrelated events that originate the question “what happens if” this or that occurrence materialize. Through these scenarios the modeler can analyze problems, threats, and opportunities that the future probable situation can exhibit. A scenario, besides plausibility and viability, must describe causal processes and be internally consistent since it is a system. Due to this, it is necessary to count with analytic, logical or mathematical models that allow guaranteeing that causal processes have an explanation between cause and effect, which can be product of rationality of social, economic or technical nature. For example, an energy intensity of families combines both aspects from the relationship between energy consumption and GDP. In the first case it is the result of individual rationality in each use, and in the second it is the technical input-product relationship as reference. By means of the analysis and contrasting of several scenarios, it is possible to generate a combination of alternatives that allow to back strategic decisions up to arrive to the desired state for the system relieving undesired effects and the uncertainty characteristic of events that can or cannot happen.

2.1. Economic Scenarios

Inside the EEDEC model two economic scenarios have been considered to model Energy scenarios: Trending and Alternative. The Trending scenario was generated based on the economic model developed in , whose characteristics are presented in Annex A of the mentioned document, and describes the inertia of the economic system between 1993 and 2013, which presumes a conservative projection for the Ecuadorian economic growth, low oil prices, and limited growth of both investments and consumption. This scenario was adjusted taking into account the GDP variations in the 2018-2021 period taken from, which consider the economic impact caused by the Covid-19 pandemics. The GDP average growth is 1.9% since 2021, up to the ending year of the study. In the case of the Alternative scenario, the GDP average growth rate was set in 2.73%, determined on the base of a possible stability that the domestic economy would present after the pandemics and reflecting the average growth rate in the decade pre-pandemics (2010-2019). In Table S.9, it can be noticed that the different sectors of the Ecuadorian economy show a relatively constant behavior through time, except for the mining sector which exhibit a significant increase in the Alternative scenario. This scenario presents this noteworthy growth rate in the mining sector based on the large-scale projects set on the government expectations about exploitation of copper and gold reserves in the country.

Table S.9. GDP growth rates projection, by sector and total in each scenario.

Scenario	Economic Sector						GDP TOTAL
	Agro-Fishing	Mining	Industry	Construction-Others	Commercial	Transport	
Trending	2.6%	2.5%	1.7%	2.2%	2.0%	1.9%	1.9%
Alternative	4.8%	17.6%	3.8%	4.3%	4.2%	4.0%	2.73%

In the same way tan with energy information, the Agriculture-Fishing, Mining, and Construction-Others, they have been integrated into a single category named Other Sectors. Figure S.39 shows the sectorial GDP projection, as well as the household consumption forecast in the alternative economic scenario.

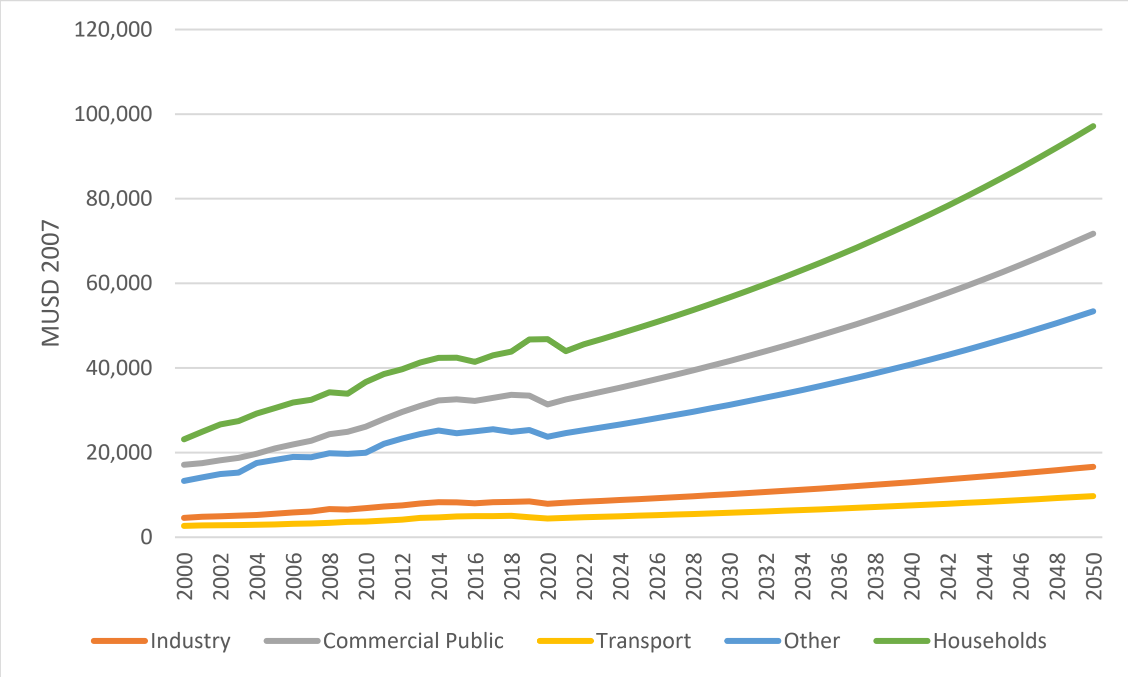


Figure 39. Projections of sectorial GDP and household consumption in the alternative economic scenario in the EEDEC model.

2.2. <u>Development of Energy Scenarios</u>

Energy scenarios are built on the base of economic scenarios. Information corresponding to the base year for energy supply and demand projections is the one included in the National Energy Balance of 2017, with its structure adapted and linked to the one defined in the economic model. Besides taking in consideration the behavior of macroeconomic trends, energy scenarios present hypotheses around the implementation of policies, or measures to substitute energy sources, penetration of more efficient technologies, increased penetration of renewables, decrease in emissions of greenhouse gases, among others. For each economic scenario, it is possible to derive not only one, but several energy scenarios. To assess the possible pathways towards an energy transition, six Energy scenarios have been developed. They consider the alternative economic scenario described in Table S.9. In this one, growth in energy consumption and supply follow trending patterns (Business As Usual). Alternative scenarios characterized by the implementation of policies oriented towards improvements in energy efficiency (improvement in intensity and source substitution, especially oil derivatives with electricity) in the consumption sectors, and the exploitation of renewable energy sources, specifically for electricity generation have been proposed. In the same way, these scenarios can include a larger availability of oil:

- *BAU_2P:* This scenario follows system current trends and maintains policies already in place. It considers a national oil availability of 7,800 MBbl.
- *BAU_O:* Similar to BAU$_{2P}$ scenario but considers national oil availability of 10,700 MBbl.

- *CEET_2P:* This is a scenario containing policies to come in a near future that will seek to reduce dependency on fossil fuels. However, targets are moderate
- *CEET_O:* Similar to CEET_2P scenario but considers national oil availability of 10,700 MBbl
- *MEET_2P:* This is a scenario containing policies to come in a near future that will seek to reduce dependency on fossil fuels. However, targets are moderate
- *MEET_O:* Similar to MEET_2P scenario but considers national oil availability of 10,700 MBbl

2.2.1. Energy Supply

2.2.1.1. Hydrocarbons reserves and extraction

Crude Oil

For crude oil reserves and extraction two cases were considered: the first one comprises total reserves (extracted and to be extracted) of crude oil corresponding to the 2P URR value used in Espinoza et al. to model oil extraction, the same study uses as base data included in the document Informe Anual del Potencial Hidrocarburífero del Ecuador 2017, which value is 7,800 million barrels. Regarding oil extraction, the median of the extraction models with best fit under URR 2P in Espinoza et al. were used, as well as the extraction profiles previously described. In order to determine the reserves to be extracted in the base year (2000), the difference between URR 2P and the accumulated extraction until 2017 was calculated, corresponding to 5,009 million barrels.

The second case takes in consideration the total crude oil reserves (extracted and to be extracted) corresponding to the O URR value used in Espinoza et al. to model oil extraction, which value is 10,700 million barrels. Respecting oil extraction, the median of the extraction models with best fit under O URR in Espinoza et al. were used, as well as the extraction profiles previously described. In order to determine the reserves to be extracted in the base year (2000), the difference between O URR and the accumulated extraction until 2017 was calculated, corresponding to 7,838 million barrels.

Non associated Natural Gas

Taking into account the methodology used in Espinoza et al [6] for the crude oil case, modelling of non associated natural gas extraction was carried out using a two-peak Hubbert approach, which generated a maximum extraction profile. The URR used in all scenarios took as reference the information of proven, probable, and possible reserves and the accumulated production included in [8], with a value of 655,414 million cubic feet.

Associated Natural Gas

In order to model the extraction of associated natural gas, the medians of the oil extraction curves for the 2P and O URRs included in were used, as no information of reserves of this resource is available. To determine, the maximum extraction profile, it was defined a ratio between historic data of oil and associated natural gas production (gas extraction/oil extraction). In this way remnant reserves of associated natural gas at base year are the product between the calculated ratio and the remnant crude oil reserves. For future extraction, the historic average value of the ratios calculated during the period 2000-2017 was used.

2.2.1.2. Production of oil products and natural gas processing

Currently Ecuador counts with a total crude oil refining capacity of 190,000 barrels per day. In all six scenarios, this capacity was defined as constant until 2050, along with the current refining profile, which has fuel oil as the product with the largest share (around 47%), followed by diesel (24%), and gasoline (19%). Regarding gas centers, it was defined that the processing capacity will remain constant from its 2017 value (11,468 million cubic feet) until 2050.

2.2.1.3. Electricity generation, transmission and distribution

Electricity generation with renewable sources

For BAU scenarios, the expansion of electricity generation has been defined using as reference the 2018-2027 Electricity Master Plan and its base case, which foresees the beginning of operations of hydro, thermal, wind (50 MW in September 2020 which would start contributing in 2021) projects, as well as of renewables block of 500 MW in 2022 [23].

For CEET and MEET scenarios, capacity expansion has considered the "Productive Matrix Case" from 2018-2027 Electricity Master Plan. This includes the introduction of additional hydropower projects tan base case, 500 MW from a mix of wind and power in 2022, and another block in 2023, followed by 50MW from Geothermal energy by 2026. For all scenarios, capacities to be installed would be 110MW of wind energy, and 200 MW of solar PV, values that are lower than the ones included in the EMP. In this case, the remaining 190 MW have not been considered given that the plan does not specify the type of technology assigned to that capacity.

Additionally, other references used were the 2017 Annual and Multiannual Statistics of the Ecuadorian Electrical Sector [24] and the 2018 Annual and Multiannual Statistics of the Ecuadorian Electrical Sector [25], with the goal of getting a clear image of the real execution of the sectorial planning. In this sense, those projects (aggregated as capacity) that came into operation in 2016, 2017, and 2018 were reviewed, and the beginning of operations of the pending projects were adjusted as shown in Table S.10. From 2018, all scenarios consider the annual growth percentage of the installed capacity according to the values included in the Table S.11.

Table S.10 Capacity additions of electricity generation renewable sources, 2017-2028 by scenarios, [M].

		Year										
Scenario	**Source**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**
BAU	**Hydro**	548.27	-	5.95	380.99	37.2	14.6	100		595.6	1200	1200
	Solar PV	-	-	-	-	200	-	-	-	-	-	-
	Wind	-	-	-	50	110	-	-	-			
	Geothermal											
CEET	**Hydro**	548,7	-	5,95	380,99	37,2	14,6	100	150	1945,6	1200	-
	Solar PV	-	-	-	-	200	-	-	-	-	-	-
	Wind	-	-	-	50	110	-	-	-	-	-	-

	Geothermal	-	-	-	-	-	-	-	-	50	-	-
MEET	**Hydro**	548,7	-	5,95	380,99	37,2	14,6	100	150	1945,6	1200	-
	Solar PV	-	-	-	-	200	-	-	-	-	-	-
	Wind	-	-	-	50	110	-	-	-	-	-	-
	Geothermal	-	-	-	-	-	-	-	-	50	-	-

Source: Own elaboration based on [23–26]

Table S.11. Annual percentage growth of the installed capacity of renewable sources 2028-2050 by scenario

Source	Scenario		
	BAU	CEET	MEET
Hydro	7.8%	9.4%	13.5%
Solar PV	69%	82.8%	119.2%
Wind	30.9%	37.0%	53.2%
Geothermal	0.0%	0.0%	0.0%
Biomass	6.1%	7.3%	10.5%
Biogas	11.3%	13.6%	19.6%

Regarding the potential of available renewable resources, for hydro, wind, solar and geothermal cases the information included in the 2018-2027 Electricity Master Plan [27] has been considered, as detailed in Table S.12. In the same way, potentials for biomass and biogas are laid out, taking as reference the Ecuadorian Bioenergy Atlas [28]. However, in this case the collection rates of agricultural and livestock residues have been defined by scenario.

Table S.12. Potential of renewable sources by scenario

Source	Unit	Scenario		
		BAU	CEET	MEET
Hydro	MWe	22,000		
Solar	MWe	16,337		
Wind	MWe	884		
Geothermal	MWe	900		
Biomass	TJ/year	92,233	230,584	230,584
Biogas	TJ/year	223.4	558.6	558.6

Electricity Generation with fossil sources

In the case of electricity generation with nonrenewable sources, it has been considered that the installed capacity will remain constant until 2017. While the 2018-2027 Electricity Master Plan incorporated the addition of 77 MW and 110 MW of thermal projects for 2020 and 2021 respectively [23], these projects have not been finished and the second one is inactive. According to press reports, it was estimated that these two projects would begin operation in 2020 and 2021, as stated in the 2018-2027 EMP [27]. However, these projects have not been considered in the mentioned scenarios. Regarding the share of fossil sources in nonrenewable generation, it was considered that the same varies according to the implementation (or lack) of a policy that that modifies the share of each source starting in 2028, and with goal to be reached in 2050. In the case of Fuel Oil share, this would depend on the targets considered around the increase or reduction for the rest of fuels. For all scenarios, the share of each fuel for electricity generation is depicted in Table S.13.

Table S.13. Share of fuels used in electricity generation in 2050, by scenario

Source	**Scenario**		
	BAU	CEET	MEET
Fuel Oil	50%	45%	25%
Diesel Oil	10%	10%	10%
Gasoline	0%	0%	0%
Natural Gas	40%	45%	65%
Crude Oil	0%	0%	0%
LPG	0%	0%	0%
Associated Natural Gas	0%	0%	0%

Electricity transmission and distribution

As in the case of electricity generation, transmission and distribution losses considered for the proposed scenarios use as reference the 2018-2027 Electricity Master Plan and the Annual and Multiannual Statistics of the Ecuadorian Electricity Sector [25,26]. For all the developed scenarios, it has been defined that total losses reach 8.92% in 2027, following the forecasts of the Electricity Master Plan [27], and keep this value until the end of the period under study.

Energy Imports and Exports

Oil and Natural Gas

In the case of oil exports, the three policies formerly described have been implemented: maximum exports, exports to cover internal demand, and reduced exports. Regarding oil imports, it has been posed as restrictive factor crude oil availability based on worldwide supply, based on the reference scenario of the MEDEAS model, and the Ecuadorian share of the global demand. Given that Non associated Natural Gas reserves available in the country are scarce, exports of this resource are not contemplated in any scenario, but imports are considered in the case that the available resource is not enough to meet the demand. Oil export policy per scenario is presented in Table S.14.

Table S.13. Oil export policy by scenario

Policy	**Scenario**		
	BAU	CEET	MEET
Maximum Exports	✓		
Reduced Exports		✓	
Oil Sovereignty			✓

Oil Products

All scenarios have as strategy the export of oil products surplus once internal demand has been satisfied. It has been considered the global availability of crude oil, which along with the share of Ecuador of the worldwide demand, a transformation efficiency factor, and the percentage share of each fuel in total imports, will estimate the amount of each oil product available for importing.

Electricity

Electricity interconnection in Ecuador occurs specifically with Colombia and Peru. All scenarios consider the complete exploitation of all the infrastructure of electricity generation so that the surplus can be exported once the domestic demand has been satisfied. There are not restrictions imposed on imports.

2.2.2. Energy Demand

2.2.2.1. Industrial Sector

Two types of policies regarding the dynamics of energy efficiency have been considered for the industrial sector. The first one encompasses the improvement of energy efficiency of the sources used currently in this sector, which comes given by four variables: the year at which the policy is initially implemented, the year at which it ends, the speed of implementation that can be fast exponential (1), linear (2), or slow exponential (3), and the maximum acceleration of efficiency improvement. In the case of BAU scenarios, it is not taken into consideration the implementation of a policy for efficiency improvement additional to the ones already in place, which are part of the Action Lines 1 and 3, of the Specific Goal 1, of the Industrial Axis of the National Plan of Energy Efficiency 2016-2035 (PLANEE) [29]. Hence, an inertial evolution of the intensities of each source used in the sector is followed. For CEET and MEET scenarios, policies for energy efficiency improvement are described in Table S.15. These policies have considered action lines from PLANEE [29] and perspectives of energy intensity improvement from [30–32]. Policies implemented for each scenario are depicted in Table S.14.

Table S.14. Energy efficiency policies in industry by scenario

Source	**Start Year**			**Implementation speed**			**Max improvement [%]**		
	BAU	CEET	MEET	BAU	CEET	MEET	BAU	CEET	MEET
Natural Gas	-	2025	2025	-	Exp. Slow	Exp. Fast	-	9.7%	9.7%
Electricity	-	2025	2025	-	Exp. Slow	Exp. Fast	-	9.7%	9.7%
LPG	-	2025	2025	-	Exp. Slow	Exp. Fast	-	9.7%	9.7%
Gasoline	-	2025	2025	-	Exp. Slow	Exp. Fast	-	9.7%	9.7%
Diésel Oil	-	2025	2025	-	Exp. Slow	Exp. Fast	-	9.7%	9.7%
Fuel Oil	-	2025	2025	-	Exp. Slow	Exp. Fast	-	9.7%	9.7%

The second type of policy implies the substitution of sources and technologies in the sector, which comes given by five variables: the year at which the policy is initially implemented, the year at which it ends, the speed of implementation that can be fast exponential (1), linear (2), or slow exponential (3), the maximum annual change between sources, and the minimal fraction of each source. For BAU scenario, no policy related to source substitution has been considered, whereas in CEET and MEET scenarios policies implemented would consider an increase in the use of Electricity, Natural Gas, and Biomass in detriment of LPG, Diesel Oil, and Fuel Oil. Table S.15. depicts the policies implemented per scenario.

Table S.15. Source substitution policies for industry by scenario

Source to introduce	**Source to replace**	**Start Year**			**Implementation speed**			**Max yearly Change [%]**			**Minimum fraction of source [%]**		
		BAU	CEET	MEET	BAU	CEET	MEET	BAU	CEET	MEET	BAU	CEET	MEET
Natural Gas	LPG	-	2025	2025	-	Exp. Slow	Exp. Fast	-	16%	16%	-	0%	0%
	Diésel Oil	-	2025	2025	-	Exp. Slow	Exp. Fast	-	13%	13%	-	0%	0%
	Fuel Oil	-	2025	2025	-	Exp. Slow	Exp. Fast	-	12%	12%	-	0%	0%
Electricity	LPG	-	2025	2025	-	Exp. Slow	Exp. Fast	-	16%	16%	-	0%	0%
	Diésel Oil	-	2025	2025	-	Exp. Slow	Exp. Fast	-	13%	13%	-	0%	0%
	Fuel Oil	-	2025	2025	-	Exp. Slow	Exp. Fast	-	12%	12%	-	0%	0%
Biomass	LPG	-	2025	2025	-	Exp. Slow	Exp. Fast	-	16%	16%	-	0%	0%
	Diesel Oil	-	2025	2025	-	Exp. Slow	Exp. Fast	-	13%	13%	-	0%	0%

2.2.2.2. Commercial, Services y Public Sector

As in the case of the Industrial sector, the commercial, public, and services sector works the two policy types previously described. For this sector, in the case of BAU scenarios, no policy related with efficiency improvement is considered, following an inertial evolution of the energy intensity. In the case of CEET and MEET scenarios, a policy of appliance substitution has been adopted in accordance with the action lines in the PLANEE for this sector [33]. At the same time, it has been taken as reference perspectives from [30,34]. Policies implemented for each scenario are depicted in Table S.16.

Table S.16. Energy efficiency policies in industry by scenario

Source	**Start Year**			**Implementation speed**			**Max improvement [%]**		
	BAU	CEET	MEET	BAU	CEET	MEET	BAU	CEET	MEET
Electricity	-	2025	2025	-	Exp. Slow	Exp. Fast	-	4.4%	4.4%
LPG	-	2025	2025	-	Exp. Slow	Exp. Fast	-	4.4%	4.4%
Gasoline	-	2025	2025	-	Exp. Slow	Exp. Fast	-	4.4%	4.4%
Diésel Oil	-	2025	2025	-	Exp. Slow	Exp. Fast	-	4.4%	4.4%
Fuel Oil	-	2025	2025	-	Exp. Slow	Exp. Fast	-	4.4%	4.4%

Regarding the policy of technology and sources substitution, for BAU scenarios no changes have been considered lined up with PLANEE. For CEET and MEET scenarios, policies have been proposed to increase the use of electricity to reduce the use of LPG, Diesel Oil, and Fuel Oil. Table S.17. depicts the policies implemented per scenario.

Table S.17. Source substitution policies for commercial-public by scenario

Source to introduce	**Source to replace**	**Start Year**			**Implementation speed**			**Max yearly Change [%]**			**Minimum fraction of source [%]**		
		BAU	CEET	MEET	BAU	CEET	MEET	BAU	CEET	MEET	BAU	CEET	MEET
Electricity	LPG	-	2025	2025	-	Exp. Slow	Exp. Fast	-	4.2%	4.2%	-	0%	0%
	Diésel Oil	-	2025	2025	-	Exp. Slow	Exp. Fast	-	4.0%	4.0%	-	0%	0%
	Fuel Oil	-	2025	2025	-	Exp. Slow	Exp. Fast	-	4.1%	4.1%	-	0%	0%

2.2.2.3. Households Sector

Households sector uses two types of energy intensity: the first one comprises the energy used in households for uses as cooking, lighting, refrigeration, among others; while the second one comprises the use of energy for transport in private vehicles and will be described in the section devoted to Transport Sector.

Regarding the dynamics of energy intensity in households, the two policy types used in industry and commercial sectors have been considered. In terms of improvement of energy intensity of the sources currently used, in BAU scenarios it will follow the historic trend supported by the government efforts driven by the initiatives: *Technological reconversion in residential lighting, and Program for the renewal of appliances with energy inefficient consumption* [35], which are only applied to electricity use. For CEET and MEET scenarios, efficiency policies implemented would have as reference the aforementioned initiatives (see Table S.18.).

Table S.18. Energy efficiency policies in households by scenario

Source	**Start Year**			**Implementation speed**			**Max improvement [%]**		
	BAU	CEET	MEET	BAU	CEET	MEET	BAU	CEET	MEET
Electricity	-	2025	2025	-	Exp. Slow	Exp. Fast	-	2.0%	3.9%

In reference to the policy of technology and sources substitution in the residential sector, this policy focuses on the substitution of LPG (used in cooking and water heating) by electricity. While the government effort *Program of energy efficiency for induction cooking and water heating* has advanced in its implementation [35,36] , results have not reflected on a reversion in the LPG consumption trend in this sector, reason why it has not been considered in BAU scenarios. This program is part of the Action line 3 of the Specific Goal 1 of the Residential, Commercial and Public Axis in the PLANEE [37]. For CEET and MEET scenarios, it has been assumed that the policy to replace LGP with electricity would be strengthened as seen in Table S.19.

Table S.19. Source substitution policies for households by scenario

Source to introduce	Source to replace	Start Year			Implementation speed			Max yearly Change [%]			Minimum fraction of source [%]		
		BAU	CEET	MEET	BAU	CEET	MEET	BAU	CEET	MEET	BAU	CEET	MEET
Electricity	LPG	-	2025	2025	-	Exp. Slow	Exp. Fast	-	1.1%	3.3%	-	0%	0%

2.2.2.4. Ground Transport Sector

Transport dynamics, as described in the model structure, was divided in households transport and commercial transport. In both cases a bottom-up approach has been implemented, in which energy intensity depends on the share of different technologies (gasoline, diesel oil, natural gas, hybrid, and electric vehicles).

Households transport

Structure of the energy intensity dynamics in transport of four-wheel and two-wheel private vehicles in households comprises the use of technologies based on gasoline, diesel oil, hybrid, and electric. In the case of two-wheel vehicles the considered technologies are based on gasoline and electricity. In the case of BAU scenarios, it has been defined that for two-wheel and four-wheel private vehicles, no policy will exist that favors an increase in the share of hybrid and electric technologies besides the initiatives already in progress, as in the case of the Action line 1 of the Specific Goal 3 of the Transport Axis in the PLANEE [38].

In this way, a historic trend around technology share in the private automotive fleet will be followed. In the case of 4-wheel gasoline, diesel, hybrid, and electric vehicles, and 2-wheel gasoline vehicles, a previous analysis was carried out to identify if there have been changes in the historic trend and thus choose the most suitable time range to continue with the inertial change.

In the case of two and four-wheel vehicles, as it can be appreciated in Figure S.40, a trend change occurs starting in 2009, from which the increase o reduction of the fleet has a less steep slope. For this reason, the time range 2009-2017 was adjusted as shown in Figure S.41. In this case, the year 2009 was used as year 1 in the abscissa axis.

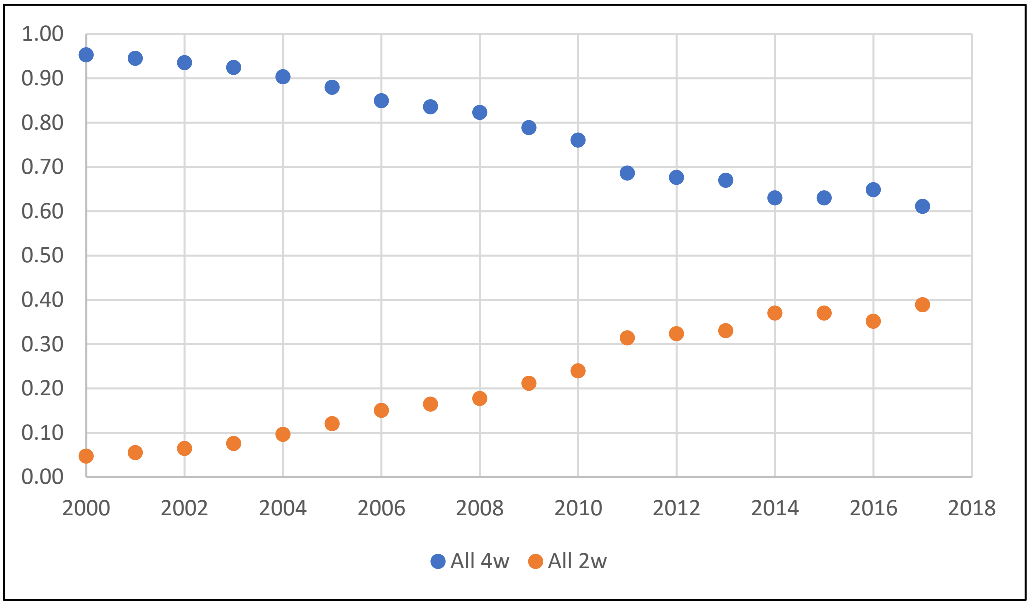


Figure S.40. Historic share (as fraction) of two and four-wheeled gasoline vehicles in the household private vehicle fleet 2000-2017

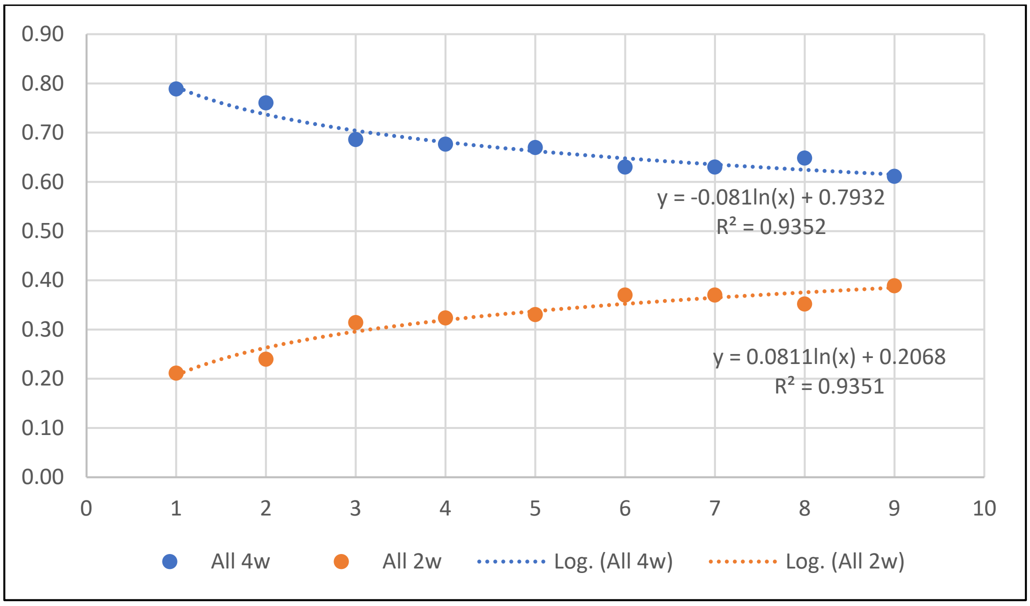


Figure S.41. Trend of the share of two and four-wheeled gasoline vehicles in the household private vehicle fleet 2009-2017

To determine the trend of the share of each technology, the mathematical function that better fits to the historic data as function of the correlation coefficient R^2 was identified. In the case of two and four-wheeled gasoline vehicles, a logarithmic function with a coefficient close to 0.94 was considered, as shown in Figure S.41.

In the case of four-wheeled diesel vehicles, a trend change was spotted from 2009 as shown in Figure S.42, reason why data from the period 2009-2017 was used, achieving a fit corresponding to a logarithmic function and a R^2 of 0.91 (Figure S.43).

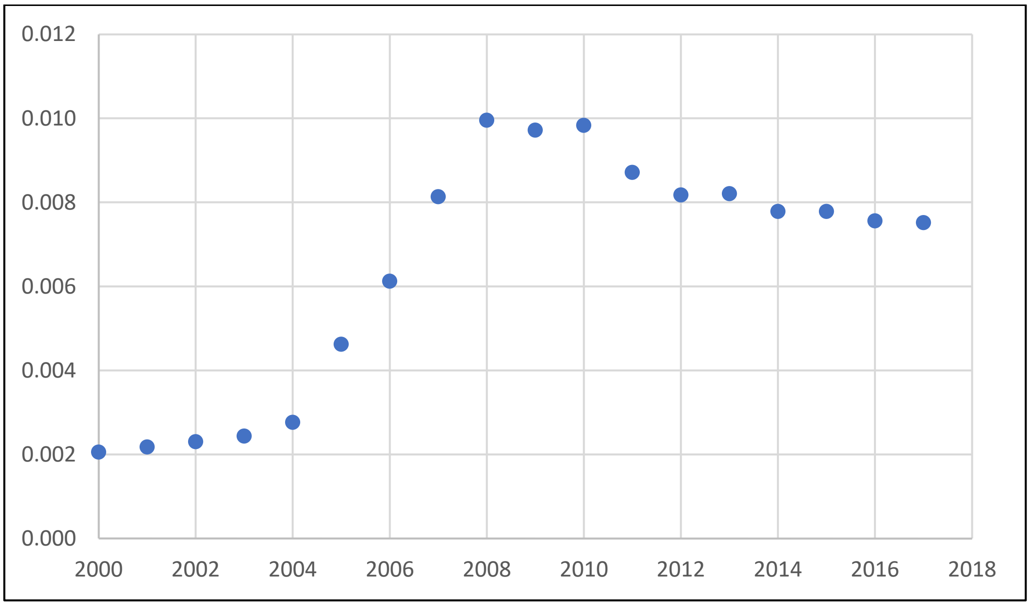


Figure S.42. Historic share (as fraction) of four-wheeled diesel vehicles in the household private vehicle fleet (2 and four wheels) 2000-2017

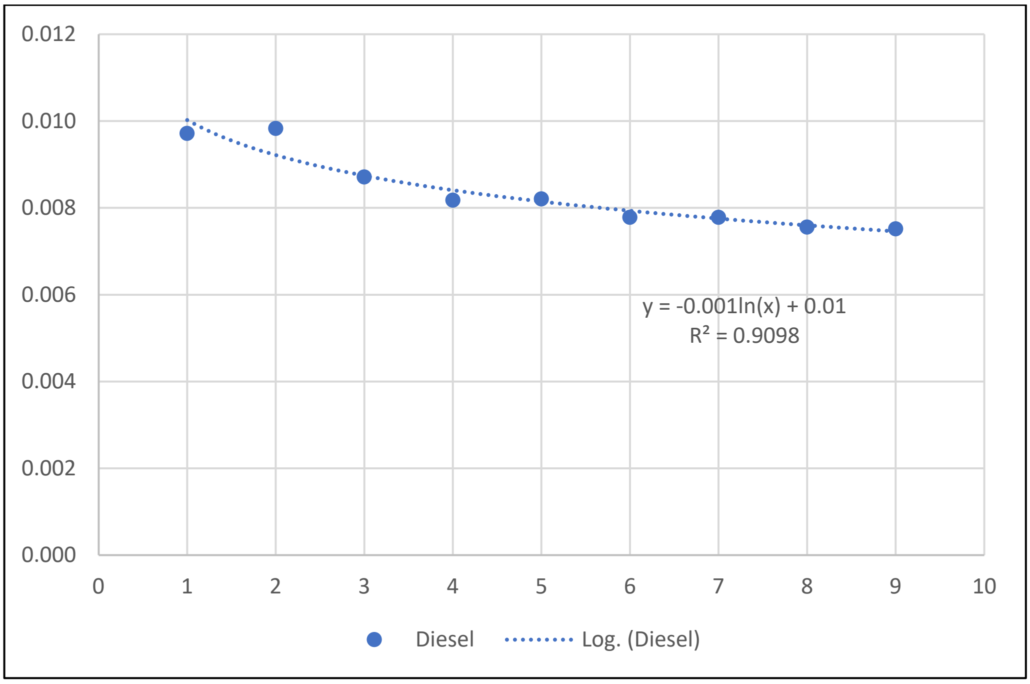


Figure S.43. Trend of the share of four-wheeled diesel vehicles in the household private vehicle fleet (2 and four wheels) 2009-2017

Trend variation of the share of these three technologies in the fleet corresponds to the derivative of the mathematical function with respect to X, variable that is found by Time-2008.

For hybrid and electric vehicles, records of their share in the household fleet exist are available from 2016 and have marginal values in the range of 1% for hybrid vehicles and 0.02% for electric vehicles. For BAU scenarios, it was considered that growth in these technologies will continue in a marginal trend, and a logarithmic function was fit to the available data. As in the case of those technologies with a larger share, the trend variation corresponds to the derivative of the mathematical function with respect to X, variable that can be defined by the expression Time-2015.

Regarding change in the share of household two and four-wheel vehicles with respect to the total fleet, in BAU scenarios the projection of 2-wheeled vehicles will follow the trend obtained in Figure 41, hence the introduction of two-wheel electric technology vehicles is discarded. According to perspectives from the IEA [39], by 2030 around 40% to 50% of the private vehicle fleet would be two-wheelers. In the case of Colombia, it has been estimated that around 70% of the fleet could be 2-wheelers by 2040.[40,41] For CEET and MEET scenarios, it has been considered the that 2-wheelers would increase its share according to Table S.20.

Table S.20. Expected share of two-wheelers in 2050 for households' transport by scenario

		Escenario		
		BAU	CEET	MEET
Vehicle type	**Two-wheeler**	38.9%	55%	60%

Several Models to estimate penetration of new technologies are available [42], among them agent-based models, consumer preference models, and rate of diffusion models and time series. Diffusion models and time series describe in general market acceptance of a product through use of theories of general market diffusion. The advantages of these models lie in their easy implementation, and their fit to historic trends of the technology or similar technologies. On the other hand, their main disadvantages lie in that the potential of maximum diffusion or acceptance must be estimated outside the model and the possible lack of historic datasets, as in the case of hybrid and electric vehicles, technologies that are still developing. Among the time series models are the Bass model, Gompertz model, and Logistic model, which have been used to estimate adoption of hybrid and electric vehicles in around 39 countries [43], Germany [44], United States [45–47], Australia [48], United Kingdom [49], South Korea [50], Denmark [51], China [52], Brazil [53] and Chile .

For the present model, it has been considered that hybrid and electric vehicle penetration will be defined through share of these technologies in the total household fleet, following a logistic function of type:

$$f(t) = \frac{M}{1+a*e^{-b*t}} \quad \text{(A.29)}$$

Where:

f(t): is the percentage share of each technology

M: is the maximum defined share percentage

a: is the slope factor

b: is the growth rate

t: is the time

In the case of Ecuador, share of hybrid and electric vehicles respect to the household fleet started to be recorded in 2017 with values of 0.5% and 0.01%, respectively. Hence, it is necessary to take reference values of available case studies for the parameters a and b, which were selected based on the studies carried out by [54]. This logistic model is used to model penetration of new technologies in both households' transport as in commercial transport for CEET and MEET scenarios.

To determine the maximum share of electric and hybrid vehicles, an analysis of the regional context was performed. Chile is one of the countries with more ambitious targets of EV share (40% by 2050). Colombia has stablished a goal of introducing 600,000 vehicles by 2030. Costa Rica is planning to have 100% electric taxis by 2050 and 60% light duty vehicles [55]. Considering as well targets used in previous works for the Ecuadorian context [56–58]. Regarding sustainable mobility, global targets have been used as reference [59]. Table S.21. depicts the maximum share of hybrid, and electric vehicles for CEET and MEET scenarios.

Table S.21. Expected share of alternative technologies in 2050 for households' transport by scenario

		Escenario	
		CEET	MEET
Vehicle type	**Two-wheel Electric**[1]	30%	50%
	Four-wheel Electric[2]	18%	28%
	Four-wheel Hybrid[2]	15%	30%
	Sustainable Mobility (e-bikes, non-Motorized)[2]	10%	20%

[1]The share corresponds to 2-wheelers
[2]The share corresponds to 4 wheelers

Commercial Transport

The structure of the energy efficiency dynamics in commercial transport includes the use of technologies based on gasoline, diesel, natural gas, hybrid an electric. For commercial transport in BAU scenarios, no policy favoring an increase in technologies of natural gas, hybrid and electric will be defined apart from the current initiatives, which focus on mass passenger transit and particularly comprise the beginning of operation of the metro system in the city of Quito and the light rail in the city of Cuenca. Regarding the share of technologies used currently, these will follow their historic trends. To determine the trends in the share of the commercial transport, the historic information of each technology was used as base and the same analysis than in the case of household fleet was implemented.

Gasoline and diesel heavy duty vehicles, as shown in Figure S.44, show an abrupt change in their trend since 2010. For this reason, the data from the 2010-2017 period was used to forecast this trend, obtaining a logarithmic function for both technologies with a correlation coefficient of 0.96 (Figure S.45). The trend variation corresponds to the derivative of the mathematical function respect to X, variable that is defined by Time – 2009.

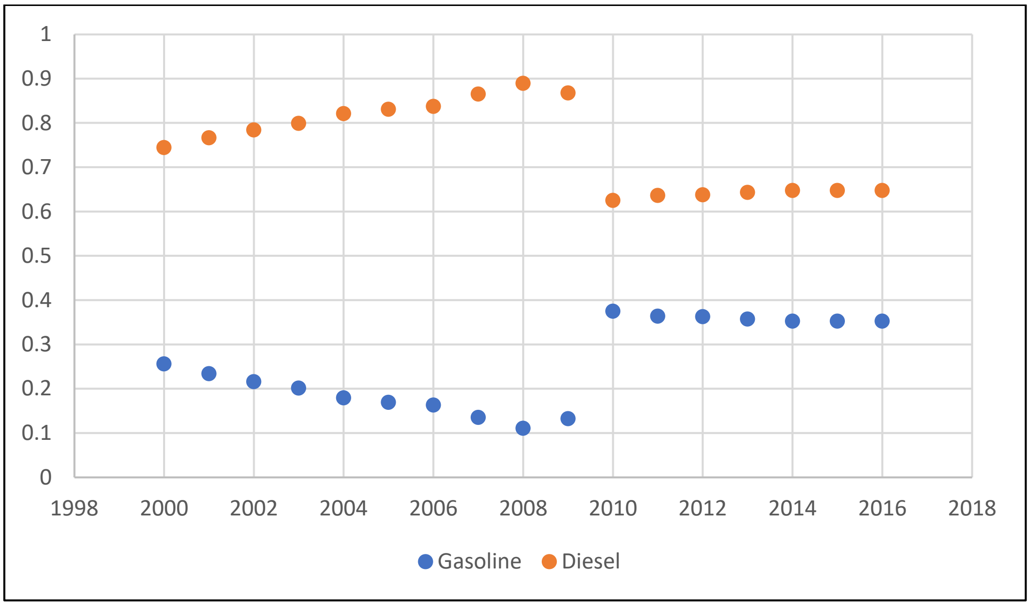


Figure S.44. Historic share (as fraction) of gasoline and diesel vehicles in the heavy-duty vehicle fleet period 2000-2017

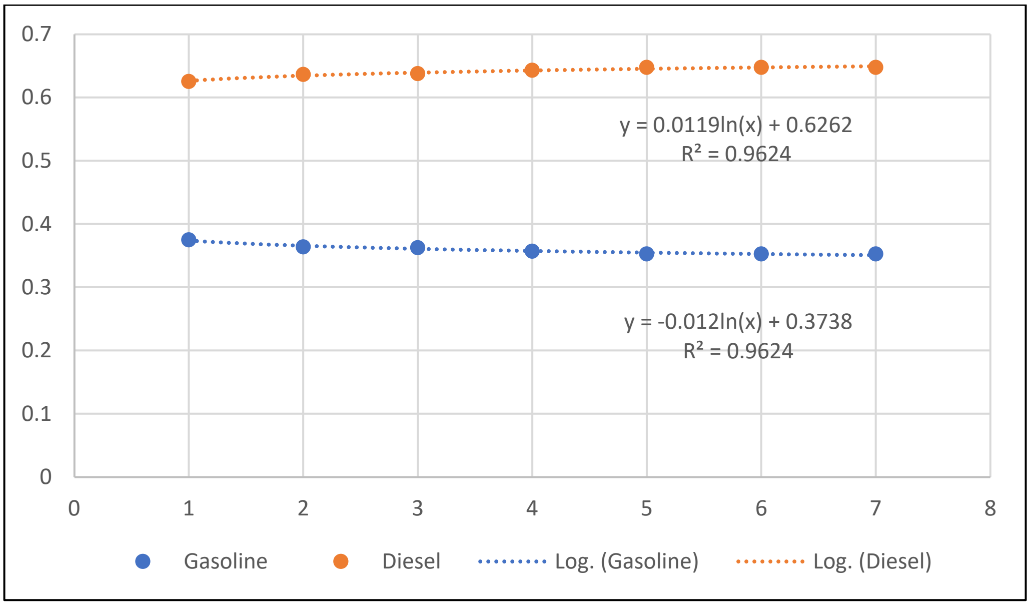


Figure S.45. Trend of the share of gasoline and diesel vehicles in the heavy-duty vehicle fleet period 2010-2017

For light duty vehicles, buses and vans, historic data show marked trends during all the 2000-2017 period (Figures A.46-A.48).

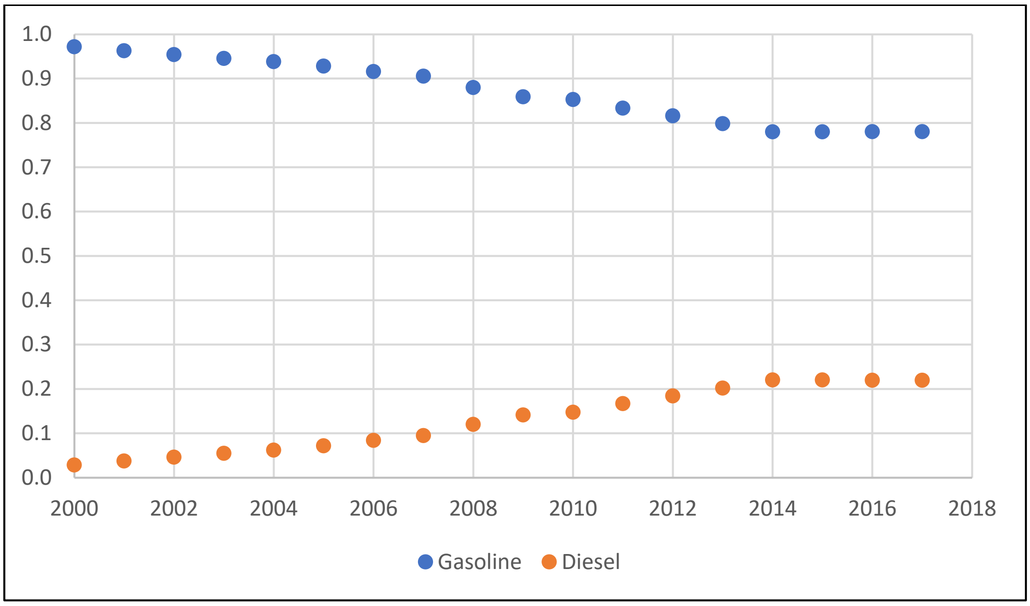


Figure S.46. Historic share (as fraction) of gasoline and diesel vehicles in the light-duty vehicle fleet period 2000-2017

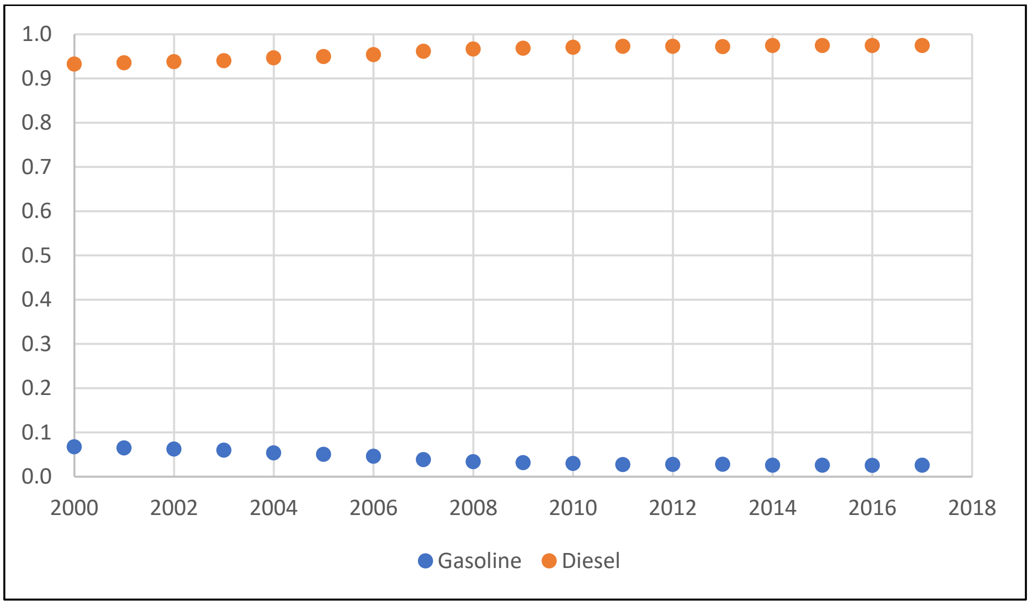


Figure S.47. Historic share (as fraction) of gasoline and diesel vehicles in the bus fleet period 2000-2017

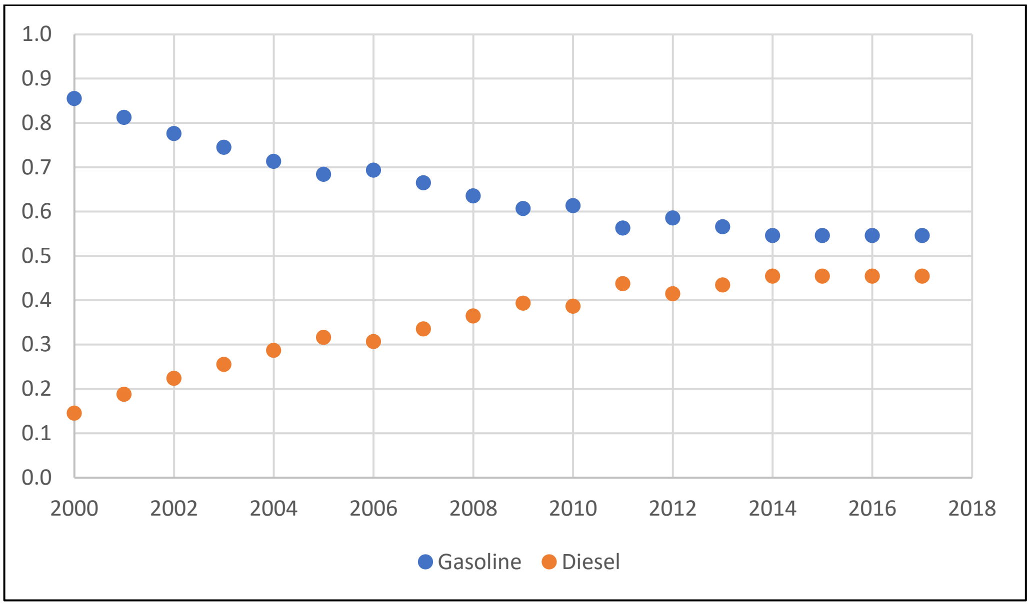


Figure S.48. Historic share (as fraction) of gasoline and diesel vehicles in the van fleet period 2000-2017

The trend in the case of light-duty vehicles obeys a linear function obtaining a correlation coefficient of 0.98 (Figure S.49), whereas for buses and vans the trend was fit to logarithmic functions with correlation coefficients of 0.92 and 0.96, respectively (Figures A.50 and A.51).

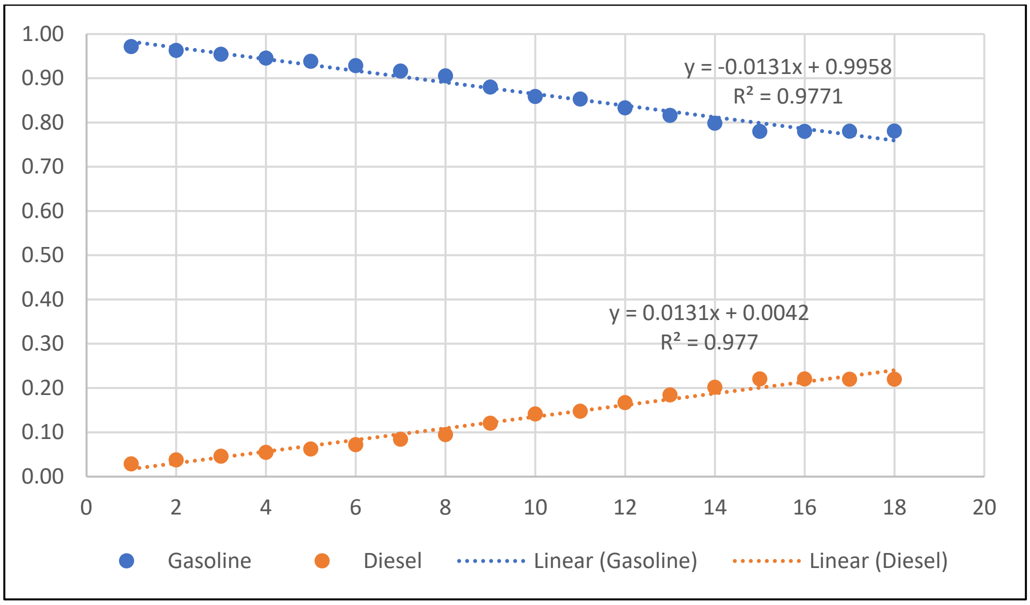


Figure S.49. Trend of the share of gasoline and diesel vehicles in the light-duty vehicle fleet period 2000-2017

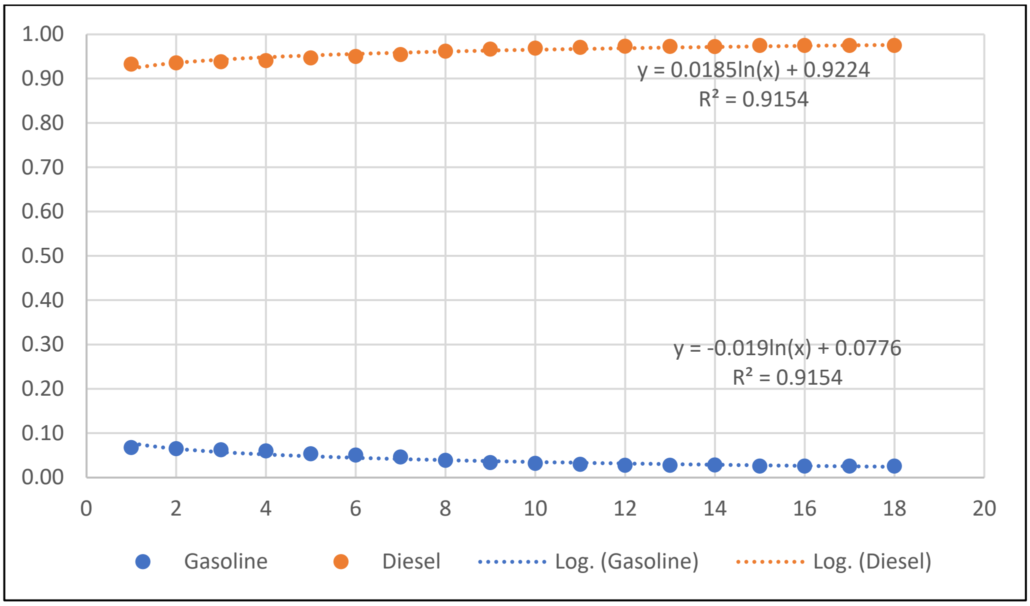


Figure S.50. Trend of the share of gasoline and diesel vehicles in the bus fleet period 2000-2017

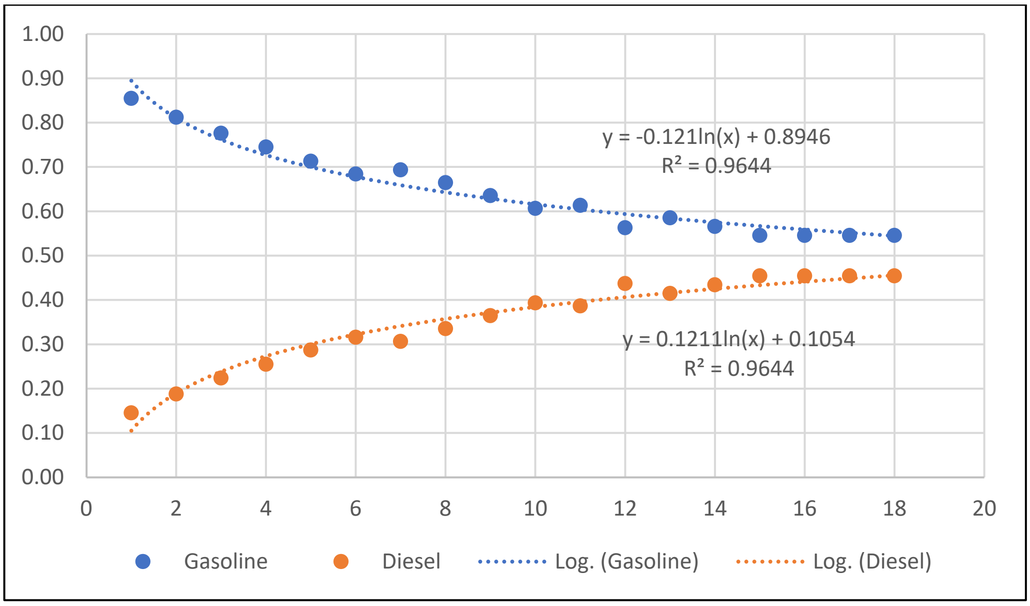


Figure S.51. Trend of the share of gasoline and diesel vehicles in the van fleet period 2000-2017

The trend comparison of the technology share in the fleet of the three vehicle categories corresponds to the derivative of the mathematical function respect to X, variable corresponding to Time – 1999.

For CEET and MEET scenarios, in the case of low duty vehicles, the same targets as in households for technology penetration of hybrid and electric 4-wheelers have been considered. All electric low duty vehicles will replace gasoline vehicles whereas 60%, and 40% of hybrid will replace gasoline and diesel, respectively. (Table S.22.)

Table S.22. Expected share of alternative technologies in 2050 for Low Duty vehicles by scenario

		Escenario	
		CEET	MEET
Vehicle type	**Low Duty Electric**	18%	28%
	Low Duty Hybrid	15%	30%

Regarding heavy duty vehicles, CEET and MEET scenarios include policies to foster the introduction of hybrid, and natural gas vehicles. Natural gas constitutes and alternative for liquid fuels such as diesel or gasoline [60,61]. Electric vehicles in this category have not been considered due to conservative projections regarding their introduction at global level (1-3% share of trucks by 2030) [39].

Table S.23. Expected share of alternative technologies in 2050 for Heavy Duty vehicles by scenario

		Escenario	
		CEET	MEET
Vehicle type	**Heavy Duty Hybrid**	5%	15%
	Heavy Duty Natural Gas	20%	40%

In the case of buses, considering the Organic Law for Energy Efficiency [62] that states that starting 2025 buses introduced will be 100% electric, CEET and MEET scenarios present the following targets in 2050. (Table S.24.)

Table S.24. Expected share of alternative technologies in 2050 for Buses by scenario

		Escenario	
		CEET	MEET
Vehicle type	**Electric Bus**	35%	85%

Regarding VANs, technologies and policy targets are the same as in Low Duty Vehicles. (Table S.25.)

Table S.25. Expected share of alternative technologies in 2050 for VANs by scenario

		Escenario	
		CEET	MEET
Vehicle type	**VAN Electric**	18%	28%
	VAN Hybrid	15%	30%

2.2.2.5. Other Transport Sector

Ground transport covered in 2017 more than 90% of the total consumption of the sector, the transport modalities: air and maritime, which are included in the National Energy Balance have been developed under a Top-Down approach in which the intensity of the sources: Gasoline, Jet Fuel, Diesel Oil and Fuel Oil, follow an inertial variation in energy intensity for all scenarios.

Top-Down approach in commercial and household transport

As part of the Top-Down approach in the transport sector, the hypothesis of substituting gasoline by ethanol has been considered for the developed scenarios. Since 2011, ethanol (from sugarcane) and gasoline have been blended as part of a pilot plan named ECOPAIS, which in 2015 was supported by a presidential decree establishing a progressive commercialization of the blend that would reach 10 % of ethanol [63]. However, the share of this source respect to gasolines consumption (gasoline + alcohol) reaches marginal values, from 0.18% in 2011 to 1.2% in 2017 [64]. In the case of BAU scenarios, the system would follow inertial trends whereas in CEET and MEET scenarios, policies would be implemented according to Table S.26.

Table S.26. Source substitution policies for transport by scenario

Source to introduce	Source to replace	Start Year			Implementation speed			Max yearly Change [%]			Minimum fraction of source [%]		
		BAU	CEET	MEET	BAU	CEET	MEET	BAU	CEET	MEET	BAU	CEET	MEET
Gasoline	Ethanol	-	2025	2025	-	Exp. Slow	Exp. Fast	-	2%	2%	-	70%	70%

2.2.2.6. Other Sectors

For the category Other Sectors, whose dynamics has the same structure as for the Industrial, Commercial, and Residential sectors, all BAU scenarios contemplate that no efficiency improvement policy or technology and source substitution policy will be implemented, thus following the historic inertia in the evolution of the energy intensity of each used source.

For CEET and MEET scenarios, policies for energy effciency have been tested based on action lines included in PLANEE for Own Use Sector [65]. Table S.27 depicts the variables used in each scenario.

Table S.27. Energy efficiency policies in Other Sectors by scenario

Source	Start Year			Implementation speed			Max improvement [%]		
	BAU	CEET	MEET	BAU	CEET	MEET	BAU	CEET	MEET
Oil	-	2025	2025	-	Exp. Slow	Exp. Fast	-	7.7%	7.7%
Electricity	-	2025	2025	-	Exp. Slow	Exp. Fast	-	7.7%	7.7%
LPG	-	2025	2025	-	Exp. Slow	Exp. Fast	-	7.7%	7.7%
Gasoline	-	2025	2025	-	Exp. Slow	Exp. Fast	-	7.7%	7.7%
Diesel Oil	-	2025	2025	-	Exp. Slow	Exp. Fast	-	7.7%	7.7%
Fuel Oil	-	2025	2025	-	Exp. Slow	Exp. Fast	-	7.7%	7.7%

Regarding source substitution in Others Sector, policies have been considered in CEET and MEET scenarios for increasing the use of electricity in detriment of Oil, LPG, Diesel, and Fuel Oil. Table S.28.

Table S.28. Source substitution policies for Other Sectors by scenario

Source to introduce	Source to replace	Start Year			Implementation speed			Max yearly Change [%]			Minimum fraction of source [%]		
		BAU	CEET	MEET	BAU	CEET	MEET	BAU	CEET	MEET	BAU	CEET	MEET
Electricity	Oil	-	2025	2025	-	Exp. Slow	Exp. Fast	-	1.1%	2.9%	-	0%	0%
	LPG	-	2025	2025	-	Exp. Slow	Exp. Fast	-	3.9%	10.4%	-	0%	0%
	Diésel Oil	-	2025	2025	-	Exp. Slow	Exp. Fast	-	2.4%	6.4%	-	0%	0%
	Fuel Oil	-	2025	2025	-	Exp. Slow	Exp. Fast	-	1.2%	3.3%	-	0%	0%

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