UNIVERSIDADE ESTADUAL DE CAMPINAS
Faculdade de Engenharia Mecânica

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Analysis of the socio-economic implications due to the implementation of the Ecuadorian NDC in the energy context

Análise dos impactos socioeconômicos devido à implementação da NDC Equatoriana em seu contexto energético

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Thesis presented to the School of Mechanical Engineering of the University of Campinas in partial fulfillment of the requirement for the degree of Doctor in Energy systems planning.

Tese de Doutorado apresentada à Faculdade de Engenharia Mecânica da Universidade Estadual de Campinas como parte dos requisitos exigidos para obtenção do título de Doutor em Planejamento de Sistemas Energéticos.

Orientador: Prof. Dr. Marcelo Pereira Da Cunha

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UNIVERSIDADE ESTADUAL DE CAMPINAS
FACULDADE DE ENGENHARIA MECÂNICA

TESES DE DOUTORADO ACADÊMICO

Analysis of the socio-economic implications due to the implementation of the Ecuadorian NDC in the energy context

Avalição das implicações socioeconômicas produto da implementação da NDC equatoriana no contexto energético

Autor: Pedro Luis Castro Verdezoto
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Dedicatoria

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Educad a los niños y no tendréis que castigar a los hombres

Pitágoras

Resumo

A emissão equatoriana de GEE foi calculada em 80.627 GgCO2-eq. Considerando o compromisso do país na luta contra a mudança climática, o Equador ratificou a Contribuição Nacionalmente Determinada (NDC) para reduzir suas emissões de GEE em 11,87% no cenário Business-as-usual (BAU) para 2025. Considerando que a categoria de energia é responsável por 64% das emissões de GEE, as iniciativas do NDC priorizam o consumo de fontes renováveis de energia e a eficiência energética.

O esquema tradicional de avaliações ambientais classifica os modelos em dois tipos: *Bottom-up* (BU) e *Top-down* (TD). Os modelos BU avaliam as opções tecnológicas e mudanças técnicas, enquanto os modelos TD são usados para avaliações macroeconômicas. Portanto, há um "*gap*" analítico entre os modelos. Este estudo propõe uma nova abordagem metodológica utilizando um modelo híbrido que considera os aspectos energético-econômico-ambientais das mudanças propostas.

O MPC3e é um modelo híbrido entre o LEAP (modelo BU) e o CGE (modelo TD) empregando um processo de "*soft-link*". A avaliação de NDC equatoriana foi desenvolvida usando o modelo MPC3e com dois cenários: BAU e NDC. Assim, sua implementação garante uma redução de GEE de 13,93% até 2025, principalmente nos setores de geração e residências, equivalente a 7.396 $GgCO_{2\text{-eq}}$. Os objetivos da NDC são factíveis, mas com uma concentração de reduções de GEE no setor de energia e uma redução de 2,29 milhões de BOE no consumo final de energia, o equivalente a 2,08% do cenário BAU.

A implementação da NDC implica um PIB de US$ 96,63 bilhões, valor 1,03% superior ao cenário BAU. O aumento da FBCF deve-se ao nível de investimento, que também gera uma redução de 2,40% na taxa de desemprego e diminui o índice de preços em 18,65%. Assim, a estrutura econômica é adequada para a implantação da NDC, mas sua viabilidade depende de garantir o consumo dos excedentes de eletricidade, seja por meio de exportações locais ou demanda interna. Neste último, o programa PEC e o transporte elétrico têm um papel importante, mas os altos níveis de investimento e as condições sociais atuais dificultariam a implementação deles.

Palavras-Chave: Modelo híbrido; Sistemas híbridos; Eficiência Energética; Mercado de carbono; Gases Efeito Estufa

Abstract

The Ecuadorian GHG emission was calculated in 80,627 $GgCO_{2\text{-eq}}$. Considering the country´s commitment to countering Climate Change, Ecuador has ratified the Nationally Determined Contribution (NDC) to reduce its GHG emissions by 11,87% percent from the business-as-usual (BAU) for 2025. Considering that the energy category is responsible for 64% in GHG emissions, the NDC initiatives prioritize the consumption of renewable energy sources and energy efficiency.

The traditional scheme for environmental assessments classifies models into two types: Bottom-up (BU) and Top-down (TD). The BU models focus the analysis of technological options and potential for technical changes, while TD models analyze macroeconomic completeness and general microeconomic issues. So, there is an analytical "gap" between the models. This study proposes a new methodological approach by using a hybrid model that considers the energy-economic-environmental aspects of the proposed changes. The MPC3e is a hybrid model that stands between the LEAP (BU model) and the CGE (TD model) and uses a soft-link process.

The Ecuadorian NDC assessment was developed by using MPC3e model through two scenarios comparing Business-and-Usual and NDC scenarios. So, its implementation guarantees a GHG reduction of 13.93% by 2025 and it is focused on power generation and household sectors, equivalent of 7,396 $GgCO_{2\text{-eq}}$. The NDC objectives can be achieved, with a concentration of GHG reductions in the energy sector and a reduction of 2.29 million BOE in final energy consumption, the equivalent of 2.08% of BUA scenario.

The NDC implementation implies a GDP of US$96.63 billion, a value 1.03% higher than the BAU scenario. The GFCF increase is due to the investment level, which also generates a 2.40% reduction in unemployment rate and decrease the price index in 18.65%. So, the productive economic is appropriate for NDC implementation, but its feasibility depends on guaranteeing the consumption of Hydropower supply, either through local exports or domestic demand. In the latter, the PEC program and electrical transportation have an important role, but the high levels of investment and current social conditions its implementation would difficulty.

Keywords: Hybrid model; Hybrid systems; Energy efficiency; Carbon emission market; Greenhouse gases

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List of Abbreviations and Acronyms

ARCONEL - Energy Regulation and Control Agency

BCE – Central Bank of Ecuador

CES – Constant Elasticity of Substitution

CET – Constant Elasticity of Transformation

CIRED – International Center for Development and Environment

CGE – Computable General Equilibrium

COP – Conferences of Parties

ETS – Emissions Trading Schemes

E3 – Energy Environmental Economy

GEM – General Equilibrium Model

GEMPACK – General Equilibrium Modelling PACKage

GDP – Gross Domestic Product

GHG – Green House Gases

GFCF – Gross Fixed Capital Formation

GTAP – Global Trade Analysis Project

IAM – Integrated Assessment Models

IEA – International Energy Agency

INEC – National Statistics and Census Institute of Ecuador

INDC - Intended Nationally Determined Contributions

IOM – Input Output Model

IPCC - Intergovernmental Panel on Climate Change

LEAP – Long-range energy alternative planning systems

LES – Liner Expenditure System

LPG – Liquefied Petroleum Gas

MACRO – Macroeconomic model

MAE – Ecuadorian Minister of Environment

MARKAL – Market Allocation

MATE – Ecuadorian Minister of Ecology Transition

MESSAGE - Model for energy supply strategy alternatives and general environmental

MEER – Ecuadorian Ministry of Renewable Sources

MERNNR – Ecuadorian Ministry of Non-Renewable Sources

MDMQ – Quito Metropolitan District

MPC3e – Central Planning Model energy-environmental-economy

NAMA - Nationally Adapted Mitigation Actions

NDC – Nationally determined contribution

OLADE – Latin-American Energy Organization

OGE&EE – Optimization of Power Generation and Energy Efficiency

PEC – Efficient Cooking Program

RE&EE – Renewable Energies and Energy Efficiency

SAM – Social accounting matrix

SEI – Stockholm Environment Institute

TIMES - The integrated MARKAL-EFOM system

UNFCC – United Nations Framework for Climate Change

List of Symbols

Bbl.	Barrel
BOE	Barrel of oil equivalent
CH_4	Methane
CO_2	Carbon Dioxide
$CO_{2\text{-eq}}$	Carbon Dioxide equivalent
$GgCO_{2\text{-eq}}$	Gigagrams of Carbon Dioxide equivalent
$GgCH_4$	Gigagrams of Methane
GgN_2O	Gigagrams of Nitrous oxide
Gm^3	Cubic gigameter
GW	Gigawatt
GWh	Gigawatt-hour
kBOE	Kilo barrel of oil equivalent
$kgCO_{2\text{-eq}}$	Kilograms of Carbon Dioxide equivalent
kW	kilowatt
kWh	Kilowatt-hour
MW	Megawatt
MWh	Megawatt-hour
N_2O	Nitrous oxide
SO_x	Sulphur oxides
$TNCO_2$	Tons of Carbon Dioxide

Summary

1. Introduction

Climate Change is the greatest challenge faced by humankind and urges global action to address its effects. Ecuador is a signatory of the UNFCCC and accepts its objectives and principles. Despite being a marginal GHG emitter, the country has to fulfill the commitments it signed for. In 2000, the Ecuadorian government presented the First National Communication, accepting that Climate Change is a reality, and validating its unusual frequency and intensity. Among the phenomenon discussed, the "El Niño" implied a huge economic loss to the country. In 2011, the Second National Communication exposed the political and technical efforts, and the administrative procedures both at national and international levels that were carried out by the National Government. The Third National Communication emphasized the importance of the energy sector as the major contributor of GHG emissions and considers the GHG removals in the Land Uses sector. The energy sector was prioritized in the government planning and it includes researches on efficiency improvements and the use of less polluting energy sources. Thus, Ecuador's Intended Nationally Determined Contribution - INDC emphasizes actions in the energy sector. In 2017, The Ecuadorian government has ratified its Nationally Determined Contribution (NDC).

The energy sector has a major role in the Ecuadorian economy, specifically the production and export of crude oil and its products' consumption. These are aspects that reflect a fast economic and energy growth, especially in middle-class families. Passenger and cargo vehicle fleets increased significantly, with annual growth rates of 10.77% and 6.02% - respectively - in the last decade. Based on historical data, 723 thousand vehicles were circulating in 2003, this number tripled by 2017.

Several questions have been raised about the NDC implementation: What are its implications for economic growth? Which sectors would be more benefit and which would be harmed? Would these policies generate new jobs? Or, a simpler question: Is the country's energy structure appropriate to achieve the NDC objectives? How should the objectives be achieved?

The answer to these questions, one needs to account for a series of economic and energy interactions. This study contributes to the debate with a new tool to evaluate climate change policies. It proposes a new approach to climate change policy analysis, through a hybridization of bottom-up (BU) and top-down (TD) models. The MPC3e is a hybrid between the LEAP model (a BU model) and the CGE model (a TD model) through a ”linking process”, both developed for Ecuadorian energy-economic conditions. The methodology *per se* raises another concern in the research process. Is it possible to have a Hybridization between technical and economic models? What would the hybridization conditions be?

The study proposes the following hypothesis: **actions in the energy sector of the Ecuadorian NDC will have positive impacts on the economic growth of the country**. To address this hypothesis, we consider the conventional macroeconomic model. We use it to analyze its main indicators: variation in GDP, creation of workplaces, and variations in the price index. The primary goal is to determine if the socioeconomic-impacts of the Ecuadorian economy are due to NDC implementation in the energy sector. This research's specific goals are: to hybridize the energy and economic models, to establish a model hybridization methodology, to calculate the variation in the macroeconomic index due to NDC implementation, and to determine the most favorable conditions. Consequently, our analysis focuses on the following research questions: (i) **Is the productive economic structure consistent with the NDC goals?** (ii) **What will be the implications on the main macroeconomic variables: unemployment rate, economic growth, and price index?** (iii) **What will be the main affected and the main benefited sectors?**

There are two main contributions of this study to the existing literature. First, a discussion is held about NDC initiatives as support for decisions maker and its economic-environmental implications. The second contribution lies in the methodological framework, as we propose a new approach to integrate the energy-economic-environmental aspects of the NDC using a MPC3e hybrid model. This study follows the standard research structure. It discusses the research problem and its importance, presents the state of the art in this area, structures a new methodology for studying this theme, and, finally, evaluates its results.

The motivation for building this tool came from the desire to improve the analysis of the economic-energy policies in Ecuador, through a planning model with an energy, economic and environmental approach. Chapter 2 analyzes the Ecuadorian GHG emission and the Ecuadorian NDC's energy policies. Chapter 3 presents a literature review of energy and economic models and the concepts related to model hybridization. Chapter 4 discusses the methodology and approach, we expanding the analysis about the soft-link between LEAP and CGE models applied to Ecuadorian conditions. Chapter 5 presents results and discussion about it the questions proposed. Finally, Chapter 6 presents the conclusions. Policies have their positive and negative aspects to them, and mitigation policies are no exception

2. Analyzing the Ecuadorian NDC

The IPCC's Sixth Assessment Report on the Physical Science basis of Climate Change unequivocally states the relationship between climate change and anthropogenic greenhouse gas emissions IPCC (2021). This topic is not new, but this relationship was addressed subtly in previous IPCC reports. The report also highlights an increase in the frequency and intensity of climatic phenomena as well as the irreversibility of certain effects. So, mitigation measures need to take on greater relevance.

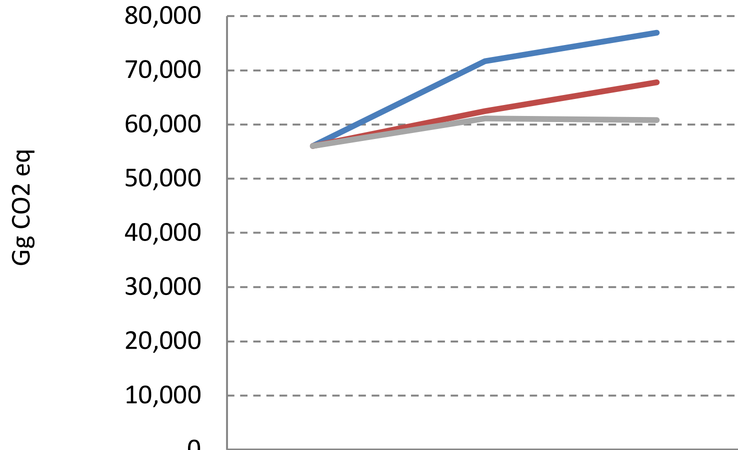
The IPCC report analyze new forecasts, one that exceeds the global warming level of 1.5 °C in the coming decades. It concludes that, unless GHG emissions are reduced immediately, rapidly, and on a large scale, limiting warming to around 1.5 °C or even 2 °C will be an unattainable goal. This condition would imply high investments in technological transitions, consumption patterns changes and other supranational agreements, bringing to the debate the need to comply with the Paris agreements.

The Republic of Ecuador responded positively to the invitation extended by COP 21 to intensify domestic actions to reduce its GHG emissions and it reflected in the INDCs. Despite Ecuador being a signatory to the UNFCCC, implementing GHG emission reduction policies are not mandatory for the country. The reason for it is the low level of emissions and the socio-economic structure allocated the country as part of the Non-Annex I list[1]. Nevertheless, there are many efforts and policies focused on fossil fuel dependency, aiming at reducing GHG emissions through national plans and strategies.

In compliance with the Paris Agreement, Ecuador's Ministry of Environment proposed the Ecuador's INDC to the international community. This agreement presents a structured trend scenario that will last until 2025, with two scenarios: the conditional contribution and the non-conditional contribution. The difference among proposals varies in support by the international community and resource availability MAE (2016). The INDC carries out an extensive qualitative analysis, including historical realities, results of previous programs, and intentional approaches. In other words, there is a minimum quantitative analysis, without exposing specific goals or specific indicators that allows for reaching the goal. This is the opposite situation when considering the energy sector, in which there are no specific goals and approaches.

In January 2018, the Ecuadorian government ratified the INDC's proposals and it became the NDC. This document presents the official commitment, updated goals, and deadlines with trending and referencing scenarios. The NDC analyzes and estimates two sections: one exclusively for the land-use sector and another for the other categories. This approach takes into account two emissions calculations. The first one is the IPCC 2003, based on land use (2008 - 2025). The second one is the IPCC 1996 by Energy, Agriculture, Industrial process, and Waste categories (2010 - 2025). The country will implement the proposals based upon a multi-sectoral participation in different administrations' levels until 2025.

[1] Non-Annex I countries are developing countries, under the Kyoto Protocol, which do not have legally binding emissions reductions targets.



	2010	2020	2025
Trend	56,038	71,641	76,904
Unconditioned	56,038	62,519	67,774
Conditioned	56,038	61,135	60,824

Figure 1 NDC's GHG emissions scenarios[2]
Source: MAE (2019)

According to Figure 1, emissions in 2010 (Baseline year) were 56,038 $GgCO_{2-eq}$, and the energy sector had a share of 64%. NDC implementation in unconditioned scenarios implies a reduction of 9,130 $GgCO_{2-eq}$ by 2025, this is equivalent of 11.87%. In the conditioned scenario, the estimated reduction is 16,080 $GgCO_{2-eq}$ by 2025, the equivalent of a GHG reduction of 20.91%. It is important to note that the NDC presents more conservative results for 2025 when compared to INDC. In case of breaching the agreements, the Ecuadorian GHG emissions would have an increase of 20,866 $GgCO_{2-eq}$ in 2025. This is the equivalent of 37.23% of emissions in 2010. Hence, the present study evaluates the feasibility and fulfillment of these objectives as well as their conditions and implications to the economy.

During COP 26, the Ecuadorian government reported the declaration of a new marine reserve in the Galapagos Islands. With 60,000 square kilometers (km^2) added to the already existing marine reserves of the archipelago, 50% of this new reserve is restricted to productive activities and the other 50% of it does not allow longline fishing MATE (2021a). This proposal is framed in a debt swap context for conservation efforts and the initiative funds are allocated to a trust for operating costs related to the marine

[2]NDC goals by Energy, Agriculture, Industrial process, and Waste sectors

reserve protection. Undoubtedly, actions of protection and preservation of marine biodiversity are appropriate. However, this approach is not part of the NDC initiatives or previous GHG reduction commitments, unaltered its goals.

Besides, a reduction of 30% in methane emissions from agriculture and electricity generation sectors is proposed by 2030. This is focused on the use of methane from sanitary landfills for electricity generation and better practices in livestock production MATE (2021b). This proposal is being evaluated by the government. This proposal is not considered in this study, because there are not a specific program to mark the route to follow its targets.

It is important to notice that the main quantifiable NDC proposals are focused on the energy sector. This is particularity due to the high levels of GHG emission in the energy sector. It means that the correct assignment of resources implies a significant GHG reduction. The specific information available for this sector allows for an estimate divided into subsectors. This argument justifies the scope of this study, as it proposes a wide analysis of the socio-economic impacts of the NDC in the energy sector. An appropriate policy in this sector implies a significant reduction in GHG emissions accompanied by economic growth.

2.1. Ecuadorian GHG emissions

The Global GHG emissions are highly related to the energy sector due to its consumption of mainly fossil fuels. They are concentrated in two main emission sectors - transport and energy generation - and they were responsible for 25% and 40% in the GHG global emissions, respectively IEA (2020). Ecuador, a country located in South America with a population of 17 million people, is no exception and approximately 50% of GHG emissions are related to the energy sector. In 1994, the first Ecuadorian inventory of GHG was presented, reporting an emission of 84,817 $GgCO_{2\text{-eq}}$. The emissions were mainly concentrated in changes in land use, a characteristic that would change over time.

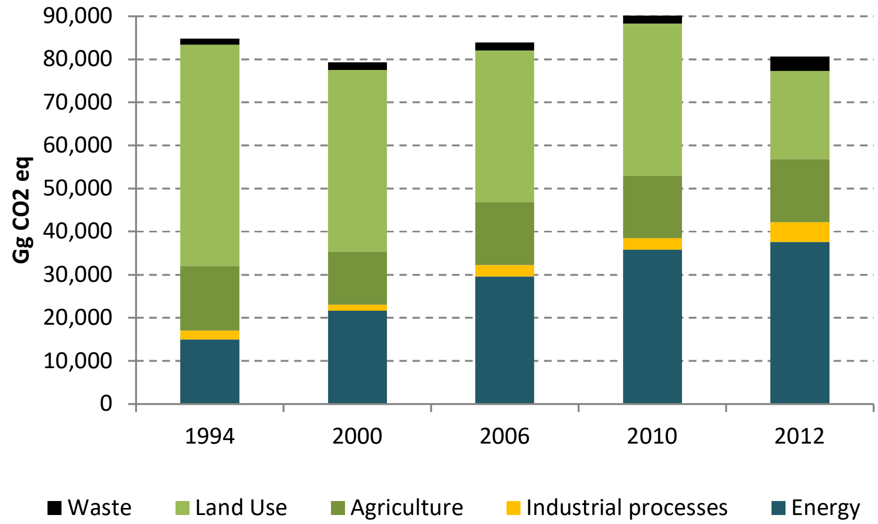


Figure 2 Trend in Ecuador's emissions 1994 - 2012
Source: MAE (2017)

Figure 2 shows that the emissions linked to the energy sector have been increasing over time. However, the emissions linked to land use have been decreasing. We highlight here that there was no significant variation in the total amount of emissions, keeping them in the range of 80,000 Gg$CO_{2\text{-eq}}$. In the latest GHG emission report, the category 'land uses' considers absorptions and reductions due to forest's and grassland's preservation. It implies a decrease in net GHG emissions due to land use by 60.18% since 1994. The third national communication on climate change, in 2017, estimated Ecuadorian GHG emissions of 80,627 Gg$CO_{2\text{-eq}}$. The energy sector was the main emitter, followed by land use (47% and 25%, respectively). The energy sector gained importance by defining mitigation policies.

The governmental policy focused on changing the energy matrix and diversifying its production. We highlight three main actions taken: new hydropower plants, new efficiency parameters for thermopower plants, and energy efficiency in households. In 2012, the energy sector had an emission of 37,594 Gg$CO_{2\text{-eq}}$. Carbon dioxide represented almost the totality of GHG emissions with a 97% share. The remaining 3% is concentrated in CH_4 and N_2O emissions. This characteristic may be different in the future, because of the construction of new hydropower plants to supply energy for local and regional markets.

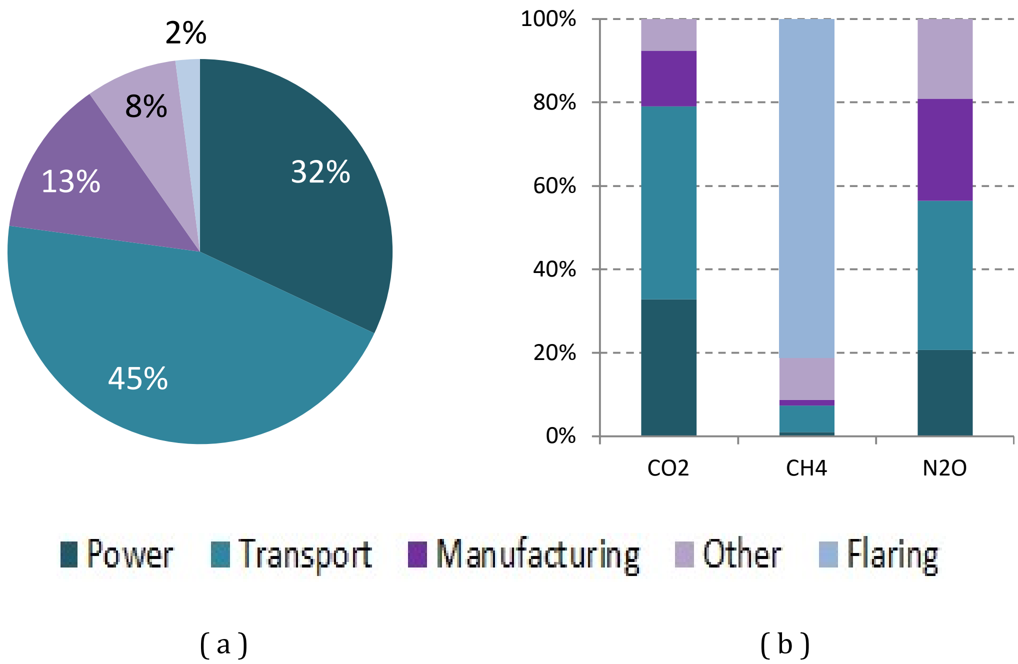
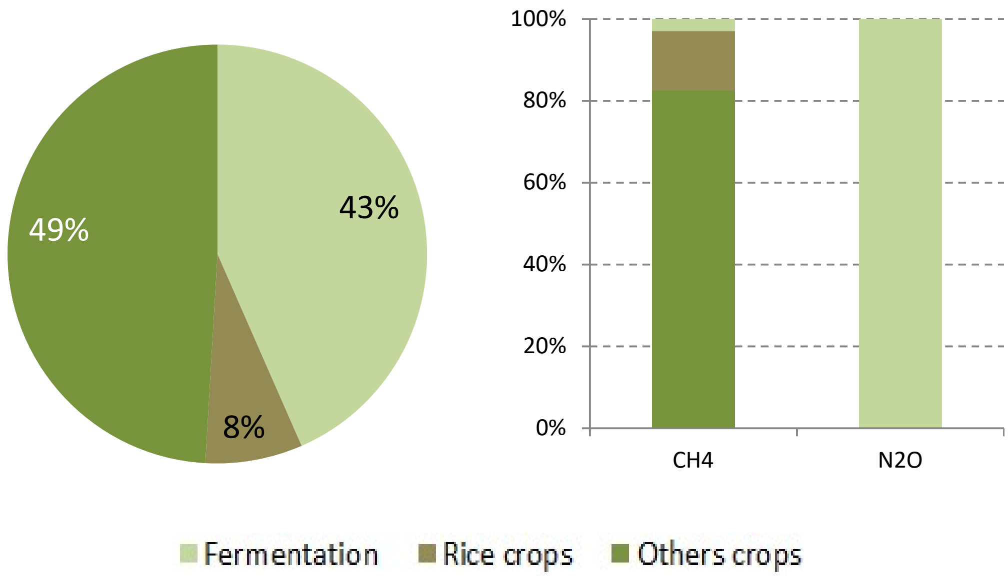


Figure 3 Energy's emissions by (a) sector and (b) GHG
Source: MAE (2017)

Figure 3a shows that more than 70% of GHG emissions in the energy sector are concentrated in electricity generation and transport. This is mainly related to burning fossil fuels, which concentrated more than 80% of CO_2 emissions. Figure 3b shows CH_4 emissions, in which burning natural gas is responsible for at least 80% of these emissions.

The agriculture sector had an emission of 14,648 $GgCO_{2\text{-}eq}$ in 2012. Fermentation and general crops were the main emitters with 92% (Figure 4a). Rice cultivation is a major agricultural product in the country and employs 411 thousand hectares with a production of 1,565 thousand TM in the same year, implying an emission of 700 $kgCO_{2\text{-}eq}$ / TM produced.



(a) (b)

Figure 4 Agriculture's emissions by (a) activity and (b) GHG
Source: MAE (2017)

Methane and nitrogen dioxide are the only GHG generated in this sector, responsible for 7,687 $GgCH_4$. and 6,960 GgN_2O respectively. Figure 4b shows that emissions are directly related to enteric fermentation (unique emitter for N_2O) and crops growing, which have the largest share of CH_4 emissions. Land use had a net emission of 20,435 $GgCO_{2\text{-eq}}$ in 2012. According to the national inventory (2017), there was an emission of 40,205 $GgCO_{2\text{-eq}}$ and absorption of 18,814 $GgCO_{2\text{-eq}}$. We emphasize that 96% of emissions are tied to farmland and 95% of absorption, to forests.

Table 1 Emission and removal in the land use

Land use categories	Emissions ($GgCO_{2\text{-eq}}$)	Removals ($GgCO_{2\text{-eq}}$)
Forestlands		- 18,814
Agriculture lands	38,911	
Grassland		- 955
Wetlands	546	
Others	747	
Total	40,205	- 19,769

Source: MAE (2017)

Forest lands in 2012 were 4.5 million hectares and it absorbed 4,127 kg$CO_{2\text{-}eq}$ per hectares. In lands used for agricultural activities, the emission was 4,511 kg$CO_{2\text{-}eq}$ per hectares. Those are very close quantities, but the larger area of agricultural land results in a greater total emission. Land use and agricultural categories are of global importance.

However, in Ecuador, the energy category would have greater implications for GHG emissions in the short and medium terms. In recent years, there has been a significant availability of information, allowing for model structuring and new policies' evaluation approaches in this sector. This study will focus on the energy category to evaluate the required policies and conditions which allowed the NDC as a sustainable development alternative that guarantees economic growth.

2.2. Energy policies of the NDC

Ecuador's NDC establishes lines of action and initiatives aiming at reducing GHG emissions. It considers two scenarios: efforts with national resources (unconditioned scenario) and international collaboration (conditioned scenario). The actions - divided by sector - were defined as organization strategies through different initiatives that promote articulation, integration, and continuity efforts. The initiatives are plans, programs, projects, actions, and measures that aim to comply with the climate change mitigation agreements. Consequently, the Ecuadorian NDC established the following lines of action for the energy sector:

- Increase the renewable and non-conventional energies.
- Encourage energy efficiency and change consumer behavior.
- Promote and implement sustainable mobility.

The promotion of renewable energy sources would be based on the hydroelectric potential and the non-conventional renewable sources, such as solar and wind energy. Change in consumer behavior would be focused on the residential sector. This would prove to be a great challenge, considering the rapid economic growth of middle-income households. The last line of action was focused on the transport sector.

Table 2 Unconditional scenario mitigation

	Initiatives	Description
1	Hydropower development	• Identify water resources for electricity generation
2	Optimization of power generation and energy efficiency (OGE&EE)	• Flare reduction • Use of associated gas for LPG production and power generation
3	Non-conventional renewable energy	• Wind and solar energy expansion • Landfill biogas development
4	Efficient cooking program (PEC)	• replace the use of LPG stoves with induction stoves for cooking
5	Efficient public transport	• Operation of Quito Subway line (22 km) • Cuenca tramway line (12 km)

Source: MAE (2019)

It is noteworthy that the initiatives presented at the NDC are descriptive and do not establish specific indicators or specific goals for each of them. This implies a challenge to quantify GHG reduction for each initiative and evaluate how appropriate are the initiatives. However, the initiatives presented in Table 2 are aligned with government planning and development plans. They guarantee compliance and the existence of resources for their execution.

According to the official information available from ARCONEL (2016), the first initiative consists of the construction of eight hydropower plants, which will be gradually incorporated into the national system, increasing installed capacity by 2,828MW. The growth in hydropower capacity implies a reduction in thermopower generation, and a decrease in fossil fuel consumption, mainly diesel and fuel oil.

The OGE&EE project consists of power generation from associated natural gas from crude oil production. This scheme supplies electricity for the Amazon region, which has the oil industry, water pumping, and isolated communities. The goal is to decrease the diesel consumption in power generation for this region.

Currently, non-conventional renewable sources (wind and solar) have marginal participation in the energy matrix. The wind potential in the short term is estimated at 884 MW and has an effective installed capacity of 21.15 MW. The solar potential is 911 MW, but the country only presents 26 MW of installed capacity ARCONEL (2016). Ecuador has no significant participation in railway transport mode, either for passengers or cargo. However, the NDC presents two local projects: a tramway in

Cuenca and a subway line in Quito. Both projects seek to improve urban mobility and traffic. It is expected that these will transport 400,000 and 120,000 passengers per day in the cities of Quito and Cuenca, respectively MDMQ (2014). These projects expect to boost mass transportation, reducing individual transport. Those also expect to reduce urban buses and their emissions related.

The fourth initiative refers to the Energy Efficiency Program – PEC. Its main goal is to replace the use of LPG for cooking and water heating with electricity. This is achieved by replacing LPG stoves for induction ones in 1.5 million households. It also expects a growth in the use of electrical equipment for water heating in 750.000 homes. According to the ARCONEL (2014), this policy is based on the availability of hydroelectric power for the forthcoming years.

The conditional scenario, which considers international cooperation, includes high levels of investments. The NDC's lines of action have the same focus of the conditioned scenario: energy efficiency, renewable energy, and transport. There are not proposals for changes in the energy matrix or productive structure variations in the society. While it is true that initiatives of unconditioned scenario are within government planning, they are initiatives in stages of feasibility, in fact their implementation would depend on the government in office. Therefore, they will not be considered in this study.

This study focuses solely on the energy sector. Its initiatives in the unconditioned scenario will be the reference to estimate the GHG reductions and its mechanisms to achieve its goals resulting from the NDC implementation.

2.3. Conclusions

Ecuador's GHG emission does not demonstrate significant increases, but there is a variation between categories due to methodological approach. The land use considers the $CO_{2\text{-eq}}$ absorptions tied to forest lands, a 48% equivalent of emissions from agricultural lands. The energy category has increased its GHG participation and became the greatest GHG emitter, with power and transportation sectors emitting 97% of $CO_{2\text{-eq}}$ emissions. Agriculture's initiatives - such as expansion of forest areas, reforestation sectors, protected areas, and reduction of deforestation - are control measures. This have a high impact on GEE absorptions, but more technological policies are needed.

The Ecuadorian NDC considers previous instruments. Hence, the government energy planning must have consistency with the NDC's goals and approaches. Nevertheless, its goals are aggregate without specification by initiative. The initiatives are majority focused on the energy sector, considering the hydropower resources. On the demand side, the main action line is the PEC program, which is in analysis by the government. Additionally, there are no more aggressive initiatives in individual passenger or cargo transportation, which are the main energy consumers and GHG emitters.

Several NDC actions are depending on the private industry. However, this does not necessarily guarantee its execution due to lack of incentives or profit. It shows that the NDC does not specify market control mechanisms or public-private strategies. Another weakness is the limited scope of OG&EE project, which is exclusive to the Amazon region. The participation of mid-sized cities in the transport sector is not considered, unlike the main ones - where infrastructure and consumption patterns already exist. The previous points are not considered in the NDC, being opportunity missed for GHG reductions.

Several methodologies had been used to analyze the NDC's implications. This study proposes an innovative methodology using a hybrid model between technical and macroeconomic models. The literature review will explore studies to achieve global GHG goals and regional or local studies, where the NDC implementations have an important role to activate it.

3. Literature Review

This chapter presents the existing literature about hybridization models and NDC assessment. The first session is an overview of energy and economic models available, along with a comparison between them. The analysis emphasizes the LEAP and CGE models, which are of particular interest to this study. The second session presents an analysis regarding hybridization methodologies. This is an innovative proposal, so we are limited by the little existing information. Consequently, all studies on model hybridization are considered, including interviews with experts and connoisseurs of the

LEAP and CGE models. Finally, the third part discusses the state of the art regarding the socio-economic implications of the NDC using hybrid models at the global, regional, and local levels.

3.1. An energy-economic models' classification

In this study, the energy and economic aspects of the model are regarded as a base for its development. Energy planning models became a standard tool for policymakers to evaluate economic, energy, technological or environmental policies. There is not a single form of classification or categorization of energy planning models[3], its classification might consider different criteria. This study is oriented to economic and engineering processes and its interaction between economy and technical assets. So, Nakata (2004) uses three categories for the energy planning models:

- Top-down and bottom-up models
- Equilibrium, optimization, and simulation models
- Typical energy-economic models

These models are used to evaluate the national energy policies, renewable energy systems, and global environment. Besides, Pandey (2002) considers that top-down and bottom-up models provide a good starting point to analyze the modern industries in developing countries.

3.1.1. Bottom-up models: Energy planning models

The temporal representation is an attribute of bottom-up models (BU) or technical models, depending on the availability of information. The BU models are structured with a high annual precision (called long-range models) and accuracy is not necessarily a virtue. Kannan, Turton, and Panos (2015) consider two temporal dimensions for the bottom-up energy modeling framework: the time horizon and the inter-annual time split. The first one refers to the number of periods and the number of

[3] To maintain a single definition, the name energy planning model refers to, energy policy models, energy systems models, energy management models and other similar names.

years in each period and the horizon depends on the study objectives. The second framework (called inter-annual time split) is related to the number of divisions, this is an important feature when balancing energy supply and demand in energy sources.

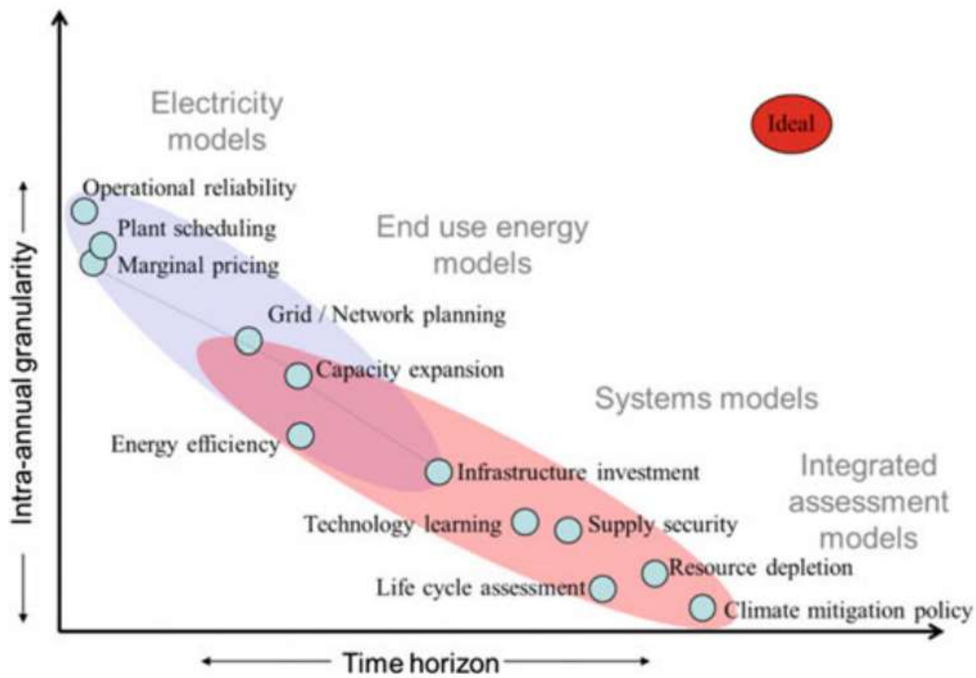


Figure 5 Temporal representation in bottom-up energy models
Source: Kannan, Turton and Panos (2015)

Figure 5 presents tradeoffs between the two temporal dimensions in energy applications. Energy planning models require a long period, as their long-term scope is used to evaluate policy implications, or structural changes. However, models with technical approaches call for an intra-annual resolution due to high levels of computational complexity. Thus, operational models and plant scheduling have high inter-annual granularity levels and a short period of analysis. This is the opposite of the integrated assessment models, in which the period is prioritized over annual granularity.

Kannan, Turton, and Panos (2015) state that there are some energy planning models being used, such as LEAP, MARKAL, TIMES, POLES, and NEMS. In consequence, Urban, Benders, and Moll (2007) suggest that only 12 energy models are suitable to developing countries., using criteria such as power sector performances, electrification, energy supply, urban-rural division, informal economy, economic structure and subsidies. According to them, there are differences between the models, especially when considering how many characteristics of developing are addressed by them. However, LEAP, MESSAGE, RETScreen, and WEM models are the ones that address large number of characteristics.

MARKAL is a bottom-up and mostly linear programming model, developed by the International Energy Agency, this model depicts energy supply and demand of the energy system, and provides information about details on energy production and consumption. It can also provide data on the relationship between economic and energy use aspects ETSAP (2016). The main variation of MARKAL is the TIMES model. This differs from its predecessor in data decoupling, allowing for flexible periods and storage process. The TIMES (The Integrate MARKAL-EFOM System) was developed by the IEA, as part of the Energy Technology Systems Analysis Program and is focused on an international community to long term energy access.

The TIMES model has a more realistic structure, as it considers investment payments and environmental assessments ETSAP (2008). The source code is distributed free, but its commercial language programming must be purchased. For the Ecuadorian case, Carvajal *et al.* (2019) use a TIMES-EC model to examine the lowest cost options for the hydropower-dominated Ecuadorian power system. They analyze the period from 2015 to 2050, in which climate change scenarios are inputs for the model. This implies that long-term hydropower will remain the most cost-effective and the lowest emission technology in the power sector.

The MESSAGE model is an engineering optimization tool used for the planning of medium to long-term energy systems. In its structure, energy demand is defined as an exogenous variable. Consequently, the model provides a framework for representing an energy system with all its interdependencies. It can show from its resource production, to imports, export, transformation, transport, and distribution. The most important application of MESSAGE so far has been in the definition of global energy scenarios. The model's loop leads to globally consistent scenarios in the development of a global energy system. MESSAGE can also be used as a stand-alone model, which means it is possible to structure regional or national applications. Consequently, models to specific countries were developed, including Syria and Brazil (Hainoun, Seif Aldin and Almoustafa, 2010; Soria *et al.*, 2016).

The LEAP model was developed by SEI and it is a widely-used software tool based upon integrated resource planning. Its focus on energy policy analysis and climate change mitigation assessment. In 2014, more than 2,000 people actively used this tool, and the LEAP online community has members in 191 countries Heaps (2018). The LEAP model was created in the context of IPCC and it was chosen by 85 countries to evaluate its mitigation policies (Bhattacharyya and Timilsina, 2010a). The LEAP became the standard tool for the GHG National communications for UNFCC.

Ecuador is a developing country; its economy depends on commodities such as oil exports and other primary products. This implies a relationship between energy consumption and economic growth Pinzón (2017). Developing countries have different energy systems and characteristics when compared to developed countries. The industrialization levels imply the existence of energy-intensive industries as well as higher quality of life and have a greater purchasing power of households (which implies different patterns of energy consumption). This implies the usefulness of energy models depends on ensuring an adequate representation of its reality. Considering the features of the models and the requirements to structure an energy planning model for Ecuadorian characteristics, the comparative analysis is reduced to three models: MARKAL/TIMES, MESSAGE, and LEAP models. They all have an approach that entails energy, economic, and climate aspects, while also being based on the demand drive concept. It means that the features of the final energy consumption define all the energy production chain.

Table 3 Select models – methodology and approach

Model	**Methodology**		**Approach**	
	Simulation	Optimization	Top-down	Bottom-up
MARKAL/TIMES		x		X
MESSAGE		x		X
LEAP	x		x	X

Sources: Szklo *et al.* (2017); Urban, Benders and Moll (2007)

The simulation in the three models requires a period, which is defined by the modeler. Their scenarios are developed using the "What if" framework[4] and investigates the effects of changes in input variables. The simulation aims to evaluate the economic and technical feasibility of a large number of technological options. It also needs to address the variations in technology and the availability of energy resources for the period being analyzed.

The module optimization is an advantage of MARKAL/TIMES and MESSAGE models, when compared to LEAP (Table 3). It is useful to compare competitiveness prices between technologies. This methodology is valid in countries with mature and competitive energy markets. This characteristic is different from developing countries, in which prices are usually regulated by the government, even though there are subsidies in the energy market. The LEAP has not an optimization module, but it is possible to structure many low-cost scenarios, simulating sectors, technologies, energy costs, and externalities for pollutants. Therefore, the decision-maker can select the most appropriate scenario.

The three models have a high versatility of geographical areas and can be used to structure national, state, or regional scenarios. The LEAP model, however, has an advantage, which is the individual assumptions per country (Urban, Benders and Moll, 2007). Due to The LEAP's versatility, it allows bottom-up and top-down hybridization approaches (Table 3). This study uses the LEAP model for Ecuador for its options of hybridization with economics models, focused on Macroeconomic Models.

About National LEAP uses, the first high-impact study using the LEAP model with national coverage was developed for Tanzania. It uses optimization models in combination with a forecasting program (Luhanga, Mwandosya and Luteganya, 1993). The LEAP was uses by Limanond *et al*. (2011) in Thailand, while Shabbir and Ahmad (2010) in Malaysia, both models evaluate energy consumption and GHG emissions. Liu *et al.* (2018) evaluated the energy consumption and pollutant emissions from China's transport sector through 2050.

[4] To refer about results or conditions that could happen in the future due to changes in trend conditions.

In Latin America, prospective study of energy consumption and power generation for Panama and Venezuela were developed by McPherson and Karney (2014), Vidoza and Gallo (2016), respectively. There are also other local studies. This is the case of the city of Medellin, which a study estimated energy demand and vehicle emissions from 2000 to 2010 (Toro-Gómez and Quiceno-Rendón, 2015). It is interesting to note that the studies presented until now are applied to developing economies. Probably, the reason is for this is the need to be more assertive in the energy resources management. The correct policy evaluation is fundamental for the decision-maker, so the LEAP model is an appropriate tool for this kind of economies.

The first applications of LEAP model for Ecuador was developed by Morales and Sauer (2001); Cárdenas (2014) to determine scenarios to reduce consumption of fossil fuels and GHG. The first case analyzes the impacts of policies giving especial attention on the residential sector, which concluded that there is a possible reduction of 6% on the total energy consumption; the second case defines energy policies in all demanding and producing sectors of the Ecuadorian society, obtaining a potential reduction of 35 million $TNCO_2$. Due to the transport sector being the main energy consumer in Ecuador, Guayanlema *et al.* (2014) reports the current status of GHG emissions caused by the transport sector, where road transports the most important in terms of CO_2 emission with a contribution of 90%.

The LEAP model is widely used for evaluating GHG reduction policies and energy efficiency policies in developing countries. The model is also used to evaluate inter-sectorial policies based on energy forecast. Several studies consider the demographic and economic growth, and technological developments, as exogenous variables to define the scenarios. The economic impacts due to policies' implementation are not evaluated by the model due to its bottom-up nature. The contribution of this study will be to complement the results of the LEAP model using macroeconomic models through their hybridization.

3.1.2. Top-Down models: Macroeconomic models

Considering the close relationship between energy consumption and economic growth in Ecuador, it is crucial to structure an economic-energy model capable of analyzing the impacts of energy policy focusing environmental assessments.

Econometrics models are an interesting option because its analysis has been defined by a combination of economic theory, mathematical tools, and statistical methods. These models provide another level of analysis. Also, they are useful for obtaining a framework about the relationship between economic development, energy index, and energy policies.

According to Keppler and Bourbonnais (2007), econometrics is a tool to unite energy and environmental changes, but the econometric models are inadequate to capture the characteristics of developing countries. This is due to the aggregate level of analysis, which is the main issue with econometric analysis of energy demand (Bhattacharyya and Timilsina, 2010b). It is inappropriate to analyze energy policies in specific sectors, such as the transport sector (the main energy consumer sector in Ecuador). These kinds of models fall into the simplicity analysis, also known as Black-box[5].

Hardt and O'Neill (2017) review modeling practices considering the economic growth and environmental aspects and they raise two types of models: analytical and numerical. The analytical models contain few equations to demonstrate fundamental relationships in the economy. The numerical models are more detailed and allow analysis of specific scenarios or even predictions. The numerical models stand out for their input-output techniques, both in monetary and physical terms.

The IOM is a numerical model, which describes the total flow of goods and services in terms of added value and specific input/output coefficients. Given the versatility of the IOM, it can be used to analyze different areas, including geographical and economic sectors to energy production. However, this model does not deal with price variation among different economic sectors.

The UNFCCC raises the importance of IAM and E3 models aim to provide policy-relevant insights into global environmental change, proposing. Several models have been proposed in this context UNFCCC (2021). From the proposed list, the use of general equilibrium models stands out, highlighting the importance of this technique for evaluating the socioeconomic impacts of environmental policies.

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[5] To refer an internal mechanism is usually hidden from or unknown to the user

The GEM are more assertive in their analysis, as they consider price variations. These types of models integrate the presumption that all markets are in perfect equilibrium, using the social accounting information to represent an initial equilibrium before a policy's implementation. The equilibrium is guaranteed by price adjustments and they cannot be influenced by internal agents, such as households, companies, and governments. The equilibrium is sensitive to price variation, and the customers try to maximize their welfare or profits. Therefore, the general equilibrium model is the most appropriate to evaluate the macroeconomic implications of the Ecuadorian NDC. To apply these concepts, this study uses a CGE model. We aim to solve numerically the levels of supply, demand and prices that support equilibrium across a set of markets.

The use of Computable or Applied General Equilibrium Models[6] (CGE) for environmental and economic analyses has grown in interest in recent years, especially to develop models that evaluate the economic impacts of global carbon dioxide reduction. These types of studies were driven by the intergovernmental agreements on climate change, such as The Kyoto Protocol and NDC. The CGE has been widely used for the analysis of the economic impacts and its relation to Clean Development Mechanism, optimal mitigation policies, transport policies, and technological changes. They are all focused on GHG emissions (Brock *et al.*, 2013; Karkatsoulis *et al.*, 2017; Timilsina and Shrestha, 2006).

The CGE model was also applied to other Latin American countries. Benavides *et al.* (2015) analyzes the economic implications of carbon taxes on the Chilean electricity generation sector. Elizondo and Boyd (2017) evaluate the economic impacts of ethanol production in Mexico and compare the effect of subsidies to initiate ethanol production with other public policies. There are no specific studies using CGE model for Ecuador regarding energy and environmental assessments. However, in 2005, the MEEGA model was developed. This model includes households, government, external sector, and industries. It is based on the social accounting matrix of 2001 and it was used to deeply discuss the impact of economic policies in the country. Its main application consisted in evaluating the effects for the Ecuadorian Economy of the Free Trade Agreement with the United States (Acosta and Pérez, 2005).

[6] To maintain a unique definition, from here the study will use the name of the Comptubale General Equilibrium (CGE) referring to applied general equilibrium modelling and all its variations.

In 2007, Ramirez (2007) developed MEGAT model, this uses the MEGGAS's structure to make a counterfactual analysis of tributary policies, considering the consumers and producer tax evasion: Add-Valorem-Tax and Income-Tax. In 2010, Cicowiez and Sánchez (2010) developed an analysis model of exogenous shock, economic, and social protection (MACEPES). It provides for Latin American countries a model to evaluate public policies and social protection. There are many applications for MACEPES to Latin America countries, including Ecuador (Cicowiez and Zamorano, 2011).

Several studies use the MACEPES to simulate social policies and include variables such as poverty and inequality (Aguiar, Gualavisí and Sáenz, 2012; Ponce, Sánchez and Burgos, 2010). Due to the model versatility, some authors also evaluate the impacts and benefits of multilateral agreements for Ecuador (Castresana *et al.*, 2017; Jácome and Cicowiez, 2012). Therefore, this study will contribute with a CGE applied to Ecuador to evaluate the impacts of environmental policies, within the NDC context.

3.2. Model Hybridization

The engineering models or conventional bottom-up models (BU) focus on detailed analysis of technological options and potential for technical changes in the energy sector. It also describes the prospective competition of energy technologies and usually presents a supply and demand sides. At first, the BU models achieve this assessment through possible substitutions between forms of energy. The demand-side evaluates assessments through the potential end-use energy efficiency, along with substitutions of energy sources. Conventional top-down models (TD) analyze the policies consequences in terms of economic competitiveness, government finances and job generation. It means that these models have a macroeconomic vision. Due to the energy aspects contemplated in the function production, energy processes are considered as a black-box.

According to Hourcade *et al.* (2006), BU models are adequate in terms of technological details for energy supply. The TD models are useful for macroeconomic completeness and general microeconomic realism, but they fail to represent the potential of different technologies. Since these two models were structured and designed based upon different approaches and for varied purposes, their conclusions and results vary a lot. Some authors refer to these variations as 'gaps', while also exploring their characteristics and possible approaches to consolidate results (Dai *et al.*, 2016; Wilson and Swisher, 1993).

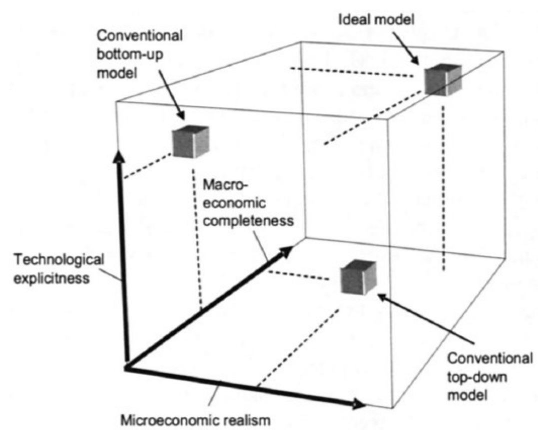


Figure 6 Three dimensional assessments of energy-economic models
Source: Hourcade *et al.* (2006)

The 'gap' results should be analyzed using an approach represented in Figure 6. In it, conventional TD models focus their analysis on policies' impacts and takes into account the micro and macroeconomic approaches. These results are based on the reaction of economic agents, quantified by elasticity. It considers the increase or decrease of both production and consumption due to price variation.

Technical disaggregation is possible in BU models, because of its demand-driven structure. It allows an analysis of technical options, while TD models consider economic sectors with a highly aggregated level assuming economic macro equilibrium. Another aspect of the BU models is the optimistic perception about the future GHG mitigation opportunities. It identifies numerous mitigation options, such as low-cost energy efficiency options. This optimistic perception is based upon the engineering perspective, based on the reduction of the efficiency gap through technological innovations. The pessimistic approach to the TD model originates from the assumption that the present technology associates the results from efficient consumers´ and producers' behavior, with prevailing economic conditions.

This study's proposal is to develop a hybrid model which includes the structural characteristics of advanced TD and BU models. This shall allow an analysis that integrates customers' and producers' behavioral parameters at the Ecuadorian economy. This model implies a greater demand in terms of structure consistency, mathematical complexity, and empirical estimation. It, nonetheless, represents a common objective of the modelers, the search for the "Ideal" model, as showed in the top back right corner of the cube in Figure 6 Hourcade *et al*. (2006).

According to Böhringer and Rutherford (2009), the models' hybridization process is categorized into three types. The first is a "Mixed complementary problems" (MCP), which combines the BU and TD characteristics directly through the specification of market equilibrium conditions. The MCP is a more recent method, but it requires robust large-scale solver.

The second type of hybridization process implies that one model should complement the other through a representation of the main parameters. This shows a dependency of one model towards another, resulting in a reductionist method. The third type of hybridization process is called "linking process", which would be either a "Soft-link" or a "Hard-link". It may face substantial problems in achieving overall consistency and convergence of iterative solution algorithms. Helgesen and Tomasgard (2018) explore hybridization methods and compare "Hard-link" and "Integrated" approaches of hybrid top-down and bottom-up models in terms of equilibrium and convergence. They find a solution by integrating the two models to reach convergence.

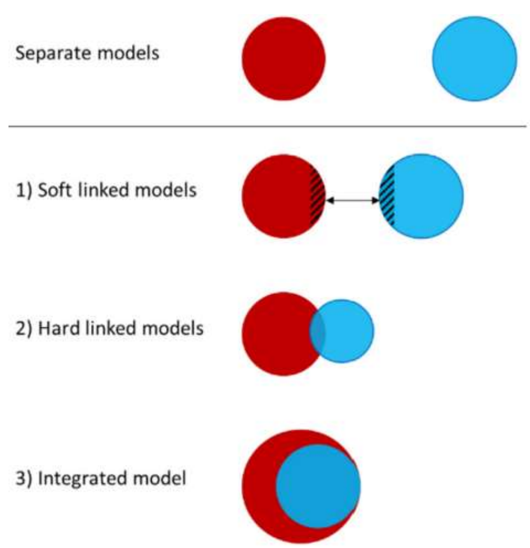


Figure 7 Different types of linking
Source: Helgesen and Tomasgard (2018)

In the “Soft-link” or informal linking, the model uses controlled processing and information transfer between the models. In it, users decide the input and output of each model, as well as the convergence. An important element is the existence of a set of common measuring points to define the input-output processing. It means creating a “plug” between both models. The feedback process is the decided by the user, and it means that the data inputs and the results depend on the user's expertise.

The “Hard-link” (or formal linking) means that information processing and transfer between models is controlled directly by computer programs. In the models’ overlapping areas, an algorithm is used to find an answer. The formal linking implies that one model has strict control over the results and the other model is set up to be a subordinate.

According to Wene (1996) practicality, transparency, and learning are the advantages of soft-linking, while the advantages of hard-linking are productivity and control. Soft linking is the a starting point for linking models based on different methodologies, which is the case for macroeconomic and systems engineering models. The advantage can be summarized in the user’s ability to analyze the results of both models, while evaluating the reasons for the non-convergence between them. This shall be used to determine the most sensitive parameters and their implications for the energy-economic relationship in this study.

As seen, there are a lot of possible combinations between models, including hybridizations and linking. These kinds of models are interesting for the policymakers to understanding and evaluate policies’ effectiveness and cost. These models are also able to analyze the proposals which seek to shift energy systems toward more environmentally desirable technologies.

The attempts to reconcile the two approaches have focused on creating hybrid models that incorporated bottom-up technologies within a top-down macroeconomic framework. Therefore, this study aims to continue with this line of research. We aim at developing a new method with integrated engineering technology and macroeconomic aspects. We will do this by exploring previous contributions and by regarding model hybridization to evaluate the socioeconomic impacts of energy and environmental policies.

3.2.1. MESSAGE – MACRO Hybridization

The MESSAGE is an important energy planning model, which hybridizes economic models. Wene (1996) structures a soft-link between a macroeconomic model (ETA-MACRO) and an engineering system model (MESSAGE III). Both of these models focus on global and environmental analysis for a scenario of 11 regions. To obtain a formal identification of areas where the models overlap, Wene (1996) defines a Reference Energy System - RES. The RES provide a fairly complete description of both the scope and technical detail of an engineering model system. The scope indicates system boundaries, along with the number of optional technologies, and alternative energy paths. The RES identifies the chain of energy technologies that convert, transmits, and distributes energy from its source to final consumption.

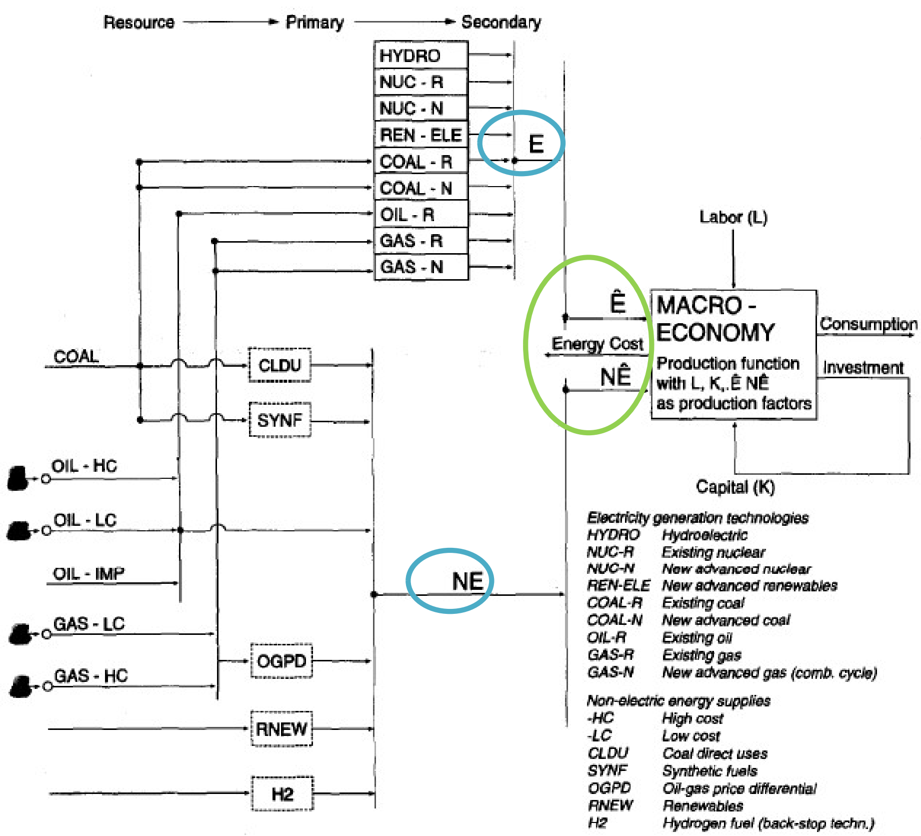


Figure 8 The Schematic diagram of soft-linking MESSAGE III – ETA MACRO
Source: Wene (1996)

The link between models is based on the physical consumption and production factors and uses energy cost as a parameter for equivalence. On Figure 8, physical consumptions are represented by ***E*** for electrical sources and ***NE*** for non-electrical resources. Production factors are represented by $\hat{\boldsymbol{E}}$ for electrical sources and $\boldsymbol{N}\hat{\boldsymbol{E}}$ for non-electrical resources. The feedback between the models links two common measuring points (CMP): electricity production and fuel demands.

The MESSAGE III model is applied to check the technical feasibility of the energy system's projects. In it, energy supply responds to prices in the form of substitution effects, which is addressed by an optimization procedure. MACRO is a macroeconomic model and it maximizes the inter-temporal utility function of a single producer and consumer in a given region. The scenario generator considers like first information the GDP for the MACRO model and final energy demand for the MESSAGE model. This information is converted in growth rates of potential GDP and rates of energy intensity reduction, which are subject to optimization in the MESSAGE III-MACRO model, giving reference values (Figure 9).

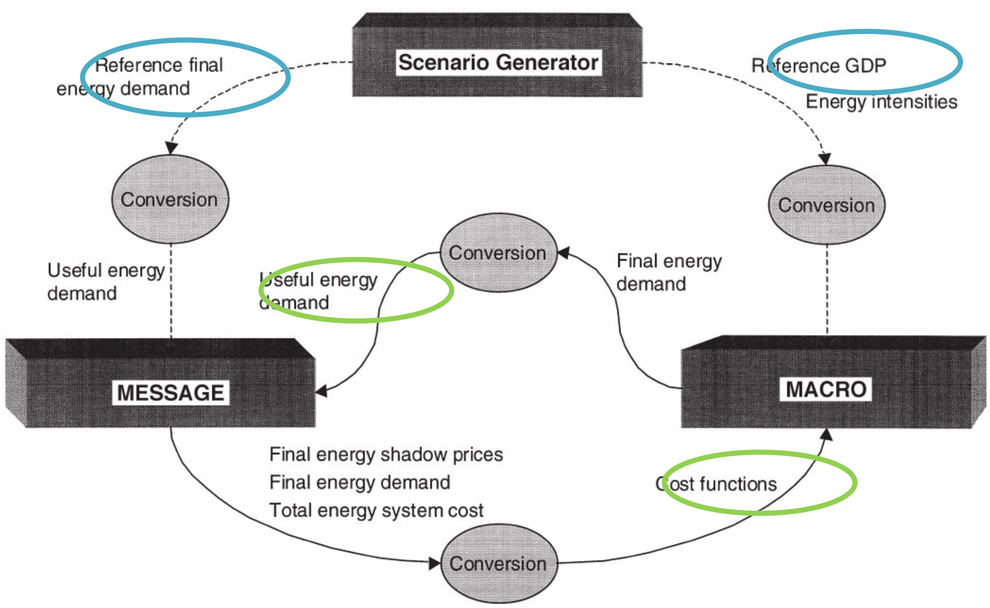


Figure 9 The Schematic diagram of soft-linking MESSAGE III–MACRO
Source: Messner and Schrattenholzer (2000)

Figure 9 presents the schematic diagram of the hybrid model. The uninterrupted lines describe the information flow during the interactions, as they connect both models based on energy demand. This is necessary for MESSAGE to drive the optimization process and provide a variable to the MACRO model. To run the iterations and obtain a correction factor, we use the final energy shadow prices, the final energy demand, and the total energy system cost (out-put MESSAGE) as data to obtain the new cost functions (input MACRO). This sequence is executed until the algorithm converges.

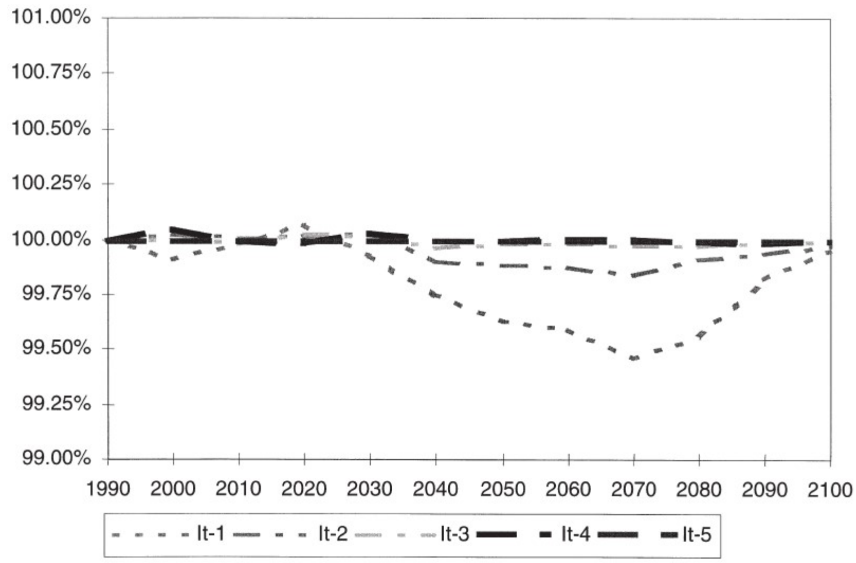


Figure 10 The iterations in the solution of MESSAGE III-MACRO: Global GDP
Source: Messner and Schrattenholzer (2000)

Figure 10 shows that the MESSAGE III-MACRO solution required five iterations and had a rapid GDP convergence with an error below to 1%. The third iteration is a standstill of the model's GDP projection. Nevertheless, the shadow prices' function has a much wider range, which obtained a convergence solution in the fifth iteration. The reason for these differences between the convergences, in the case of the GDP, is due to the small fraction of economic output that is used to pay for the energy supply of an economy. In the shadow prices, this is the reason for the interplay between electric and non-electric energy in the production function of MACRO, which allows substitution between these two energy forms.

3.2.1. CGE – TIMES_PT Hybridization

The effectiveness of energy-economy-environmental models to develop cost-effective climate policies require us to consider demographic, economic, and technological issues. Simoes *et al.* (2015) use the TIMES model as a framework to address climate policy issues and proposes using this model to assess the effects of exogenous assumptions in GHG emissions forecasts in Portugal. The TIMES_PT compares six scenarios, where the first main conclusion is that key issues in energy supply in Portugal, the availability of water for hydropower, and the price of to be imported oil, hardly have any influence on the outcomes in terms of greenhouse gas emissions in 2020.

To overcome the main limitations of the CGE models, Fortes *et al.* (2014) propose a hybrid platform called HYBTEP (Hybrid Technological-Economic Platform). This Hybridization is defined by single country version of two models: TIMES_PT and GEM-E3_PT. It corresponds to Portugal and covers all aspects of its economy. It is based on 2005's data and combines the Portuguese SAM with national statistics. The link between the two models requires the establishment of a coherent data structure. Due to the focus on different activities and actors in the energy sector, it implies a convergence between the variable models among energy issues.

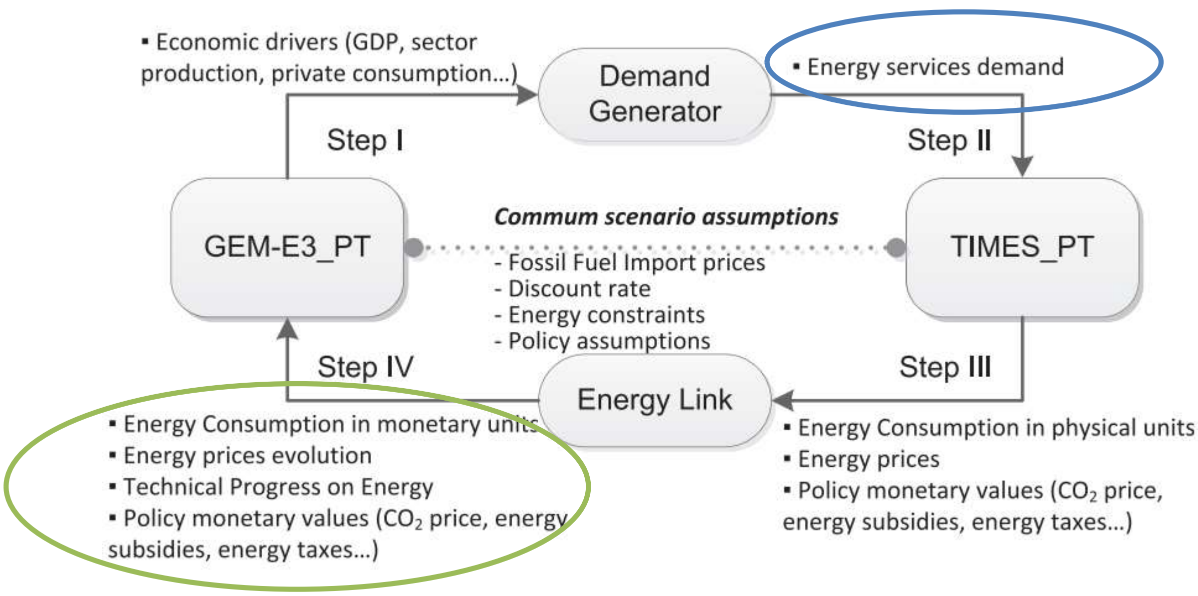


Figure 11 Schematic view of HYBTEP soft-link framework
Source: Fortes *et al.* (2014)

Figure 11 shows the initial conditions raised for CEM-E3_PT. It shows exogenous variables such as energy import prices, energy constraints, population growth, technical progress, and expectations on future sector-specific growth. The model projects energy services and materials demand (named demand generator module) and establishes the initial drivers to the TIMES_PT model. They create the energy link module by using inputs from GEM-E3_PT, which executes the new input conditions to calculate the new output conditions, during a given cycle of iteration.

To evaluate the convergence level of both models (GEM-E3_PT and TIMES_PT), they created a calibration scenario. This is used as the starting point for the subsequent policy simulations. Figure 12 shows the HYBTEP iterations in the calibration scenario (CALIB). To guarantee the convergence between models, they needed three iterations, where $D_{j,t}$ represents the demand for each energy service, material, or mobility *j,* in the period *t.* D_{j2005} refers to the conditions in the base year.

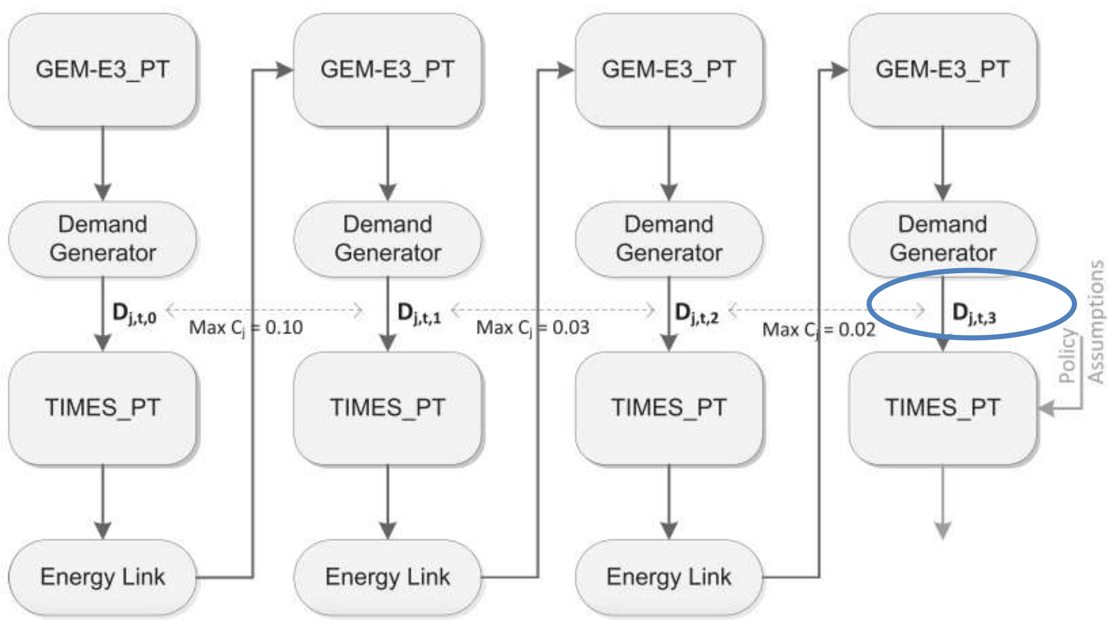


Figure 12 Schematic view of HYBTEP iteration process for the CALIB scenario
Source: Fortes et al. (2014)

The CALIB scenario reflects the evolution of the Portuguese economy and energy system in absence of any energy and climate policy constraints. This Scenario is different from the typically business-as-usual scenario, as TIMES_PT presents the results taking into account an energy system's optimization. The demand for energy services results from the calibration process and its uses for environmental policy simulations, labeled as $D_{j,t,3}$. It represents an equilibrium between the energy system model (TIMES_PT) and the macroeconomic model (GEM-E3_PT). The model convergence is defined by the "convergence function per demand category (*Cj*)", where the iteration stops in a minimum energy service demand difference Fortes *et al*. (2014).

3.2.2. IMACLIM – LEAP Hybridization

The CIRED developed the IMACLIM model in the early 90s. It combines the macro-economic analysis with a sectional-engineering approach to evaluate the long-term economic pathways and policies focused on sustainable development. There are currently two versions available for this model, the IMACLIM-S and the IMACLIM-R. The former is static and the latter is a recursive version. IMACLIM-S projects the economy of a country or region, and it is particularly used to assess the macroeconomic impacts of a carbon constraint. IMACLIM-R projects the economy in a series of annual static equilibrium, whose evolution is guided by demographic trends using a disaggregation in 12 economic sectors. It is used to make long term evolution of energetic systems scenarios and evaluates GHG reduction emissions CIRED (2019).

The IMACLIM-S is a hybrid general equilibrium model. It is based on the Walrasian equilibrium and has a dual quantity-economy accounting framework. It accounts for economic and physical flows (e.g. annual production). They are balanced and linked by a consistent prices system, which relates to the energy-GHC emissions economy system, as the macroeconomic impacts the environmental and low carbon policies. Consequently, it uses an annual base representation. Its structure has many types of sceneries to evaluate different policies, while also comparing firms and customers' behavior, a characteristic also presented in the LEAP model.

IMALIM's hybridizing process was addressed by LeTreut (2017a) and Lefèvre *et al.* (2014). They focused on energy-economy-environmental assessments. Both propose and give details about an innovative procedure for building hybrid input-output matrices at the country scale (Figure 13). They applied it for France, articulating coherently the economic framework of national accounts with physical flows, based on sectorial databases. According to Lefèvre *et al.* (2014), the magnitude of the impacts varies with the modeling assumptions about technological change and the macro functioning of the economy. It also accounts for the levels of aggregation of productive sectors and other economic agents, with the specific data at hand. When comparing the standard classic CGE model with the hybrid CGE model, their differences are expanded by the use of bottom-up models, along with engineering expertise. The functions are calibrated on econometric estimations.

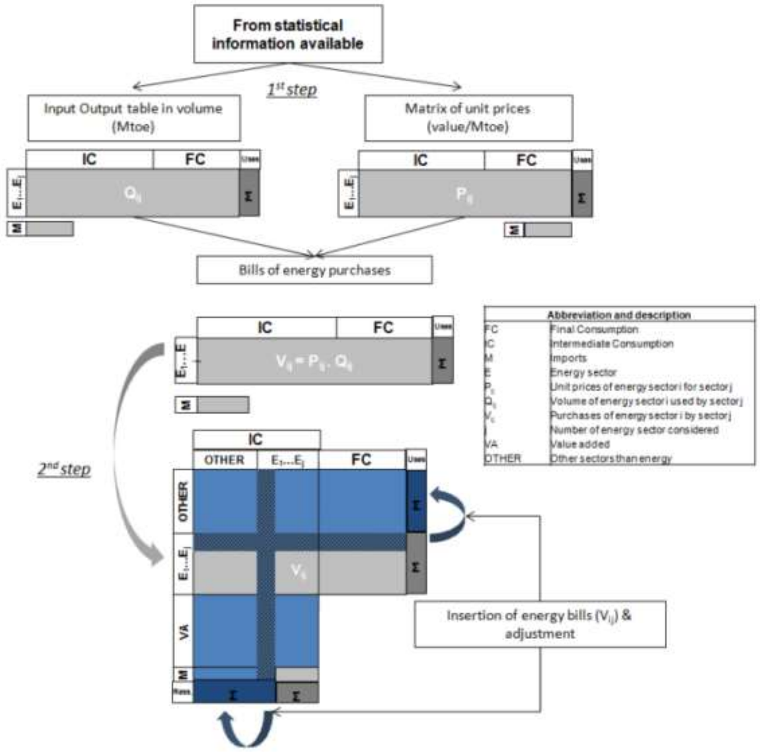


Figure 13 Overview of the IMACLIM hybridization procedure
Source: Lefèvre *et al.*(2014) and LeTreut (2017)

The data hybridization method used for the IMACLIM model aims to improve the integration of energy statistics with the macroeconomic frameworks. According to LeTreut (2017), the hybrid method follow two main steps: i) the value-added of energy production is deduced from energy prices statistics, and are not taken from the national accounts; ii) They consider the net-of-taxes purchasing price heterogeneities of the economic agents and reflects it in the energy statistics. The aim was to build a hybrid model to articulate energy system and economy-wide representations to explore energy-climate economy futures and policies, providing a better alternative to E3 models[7]. LeTreut (2017) considers that, in a globalization context, emissions from the import of goods and services from the country are ignored. Imports involve emissions abroad, so they are counted out of the national inventory scope. This problem is addressed by the hybrid method, as it shows that consumption-based emissions are higher than production-based emissions. Therefore, it would be desirable to implement a border tax adjustment for carbon emissions.

[7] E3 models refers to models bottom-up and top-down with energy-economic-environment approaches

There are two contributions of hybridization between the IMACLIM model and energy prospective models. Wills (2013) models the long-term effects of mitigation policies on the Brazilian economy based on the IMACLIM-S BR model. In this study, he explores hybridization between the MESSAGE model and a hard link, as it is assumed that both models can exchange information in terms of physical flows relative to the quantities of energy tied to its monetary values. Wills (2013) observes the importance of a robust description of the behavior of the productive sectors concerning climate policy. Despite, the MESSAGE modeled only after the electric sector, it was possible to verify the impact of its optimization capacity. It reflects a cost reduction and GHG emissions, a burden relief represented by climate policy to other sectors.

The CIRED in cooperation with the Bariloche Foundation, is developing a LEAP-IMACLIM hybridization model applied to Argentina BID (2020). Its inputs are the Social Accounting Matrix with the National Energy Balance of the Country. The methodology consists of creating a hybrid matrix that considers the disaggregation of energy sectors. They are based on their physical and monetary information, a scheme similar presented in Figure 13. The new hybrid matrix would consist of 19 sectors, meaning that there are 06 additional sectors to the current Argentinian SCM.

The Argentinian energy balance presents significant disaggregated information, it allows us to obtain data about the production, import, export, costs, sales, prices, and so on. This is used to structure six new sectors. In the structure of the IMACLIM model, the MCS is replaced by a hybrid matrix, following the scheme of Figure 13. This implies an increase on the number of variables in the model, and the structure of new equations that govern the behavior of the Argentinian energy sector.

The LEAP can obtain National Energy Balances according to different scenarios evaluated. In this Balance, the variable responses refer to energy changes. This information would be used in the hybrid matrix to determine the economic implications. Considering that LEAP is an energy-environmental model, it responds to structural changes in the technical aspects of the six additional sectors. This defines the new equilibrium conditions in the IMACLIM model. The hybridization needs to be based on model integration (Figure 7), in which the dialogue between models is executed through the script them.

The methodology used for LEAP-IMACLIM hybridization was applied and validated in other hybridization processes by previous authors, such as Lefèvre *et al.* (2014) and LeTreut (2017a). The information presented in this section was obtained during work and training sessions with the researchers from the Bariloche Foundation. The CIRED-Foundation Bariloche cooperation has so far been the most avant-garde pioneering of LEAP-CGE hybridization. This was the motivation for this study, a contribution to the science of model hybridization. However, there are differences between the methodologies applied. The LEAP-IMACLIM hybridization considers integration of models, but this study considers a soft-link methodology to LEAP-CGE hybridization. This allows a discussion and a comparison of results between both methodologies. This study structured a hybrid model based on the Ecuadorian economy to determine the socio-economic implications of environmental policies, as its NDC implementation.

3.3. Impacts of the NDC – Similar studies

In the previous section, we presented studies and documents that propose using models to evaluate energy or environmental policies. In this section, we introduce studies that address the assessments through integral models. This model builds a soft-linking between "bottom-up" and "top-down" models, assessing the socio-economic implications of NDC implementation in different countries or regions. There are – to the best of our knowledge – few studies in this area of knowledge, which justifies this study.

There are global studies about NDC's implications written by Hof *et al.* (2017), Fragkos *et al.* (2018), and Siriwardana *et al* (2021). The former uses an integrated assessment model (IMAGE) to estimate the annual reduction cost to achieve NDC targets. The second one uses a climate-change policy version of the GTAP-E model of the world economy to analyze the economic and environmental transitions for selected regions. The latter uses an economy-wide global CGE model to quantify policy impacts to NDC, by combining scenarios of ETS.

Hof *et al.* (2017) consider the uncertainty in socio-economic developments and corresponding baselines to emission projections. For it, they use different Shared Socioeconomic Pathways (SSP), which are assessments based on the reference SSP1

(Low), SSP2 (Middle), and SSP3 (High) scenarios for change mitigation. These scenarios were previously implemented in the IMAGE model, projecting future energy and land use pathways for 26 world regions, and cost cutting to keep the global warming below the level of 2 °C. The NDCs proposes a GHG reduction range from 10% (unconditional SSP1 scenario) to 17% (conditional SSP3 scenario), below the baseline levels, the reduction is mainly focused in OECD90 countries.

Fragkos *et al.* (2018) explore policy impacts of NDCs by combining a set of technology-rich country-level models for the six major world economies (Brazil, China, EU, India, Japan, and USA), with an economy-wide global CGE model (GEM-E3). They use national energy-economic models, which represent more than 60% of global CO_2 emissions. They analyze energy system transformation, economic restructuring, employment, CO_2 emission trajectories, and bilateral trade agreements. The model is calibrated on a SAM for every territory and designed to evaluate energy and environmental policies such as carbon taxes, pollution limits, RE&EE policies. The GEM-E3 simulates the production power sector through a Leontief production function, with zero elasticity of substitution among inputs. Energy intensity improvements replicate the projections of national energy models through the calibration of energy savings parameters. Fragkos *et al.* (2018) evaluate two scenarios a business-as-usual) and a NDC implementation. The first one is a projection of future global energy-economy system, based on historical system tendencies, along with the continuation of current policies. The second one assumes the implementation of conditional NDC, which was submitted to the Paris Conference.

Siriwardana and Nong (2021) focused on market-based mechanisms, particularly ETS to achieve the proposed mitigations for major emitter regions. They use three scenarios: national policies, bilateral and global cooperation. The model uses a Leontief function and constant elasticity of substitution to model the behavior of costumers and firms. For the analysis of NDCs, Siriwardana and Nong (2021) formulate three scenarios: each of the regions with domestic ETS, five regions, and seven regions form a linked international ETS. They conclude that establishing domestic ETS in each region provides conditions to meet the NDC targets. Also developing countries such as China and India experience very low abatement costs relative to developed economies due to their input costs are low, such as: labor and capital.

There are regional studies about NDC's implications written by Postic *et al.* (2017), Dai *et al.* (2018), and Misila *et al.* (2020). Based on the energy prospective approach, Postic *el al.* (2017) evaluate the impact of NDC in Latin American countries. They use a TIMES model for it and this bottom-up model describes the whole regional energy system from resource extraction to end-use energy demands, known as the Reference Energy System. This highlights renewable energy potentials, an important characteristic when seeking to reduce the economic impact.

Dai *et al.* (2018) study the economic impact of achieving Chinese's INDC through ETS and renewable energy policy. They use a CGE model and construct 14 mitigation scenarios with the following criteria: carbon reduction target, carbon emission cap, renewable energy development, and emission policy changes. Misila *et al* (2020) analyze potentials of GHG reduction during 2015–2050 based upon the use of RE&EE using LEAP model to achieve Thailand's NDC. They conclude that, to meet 20% GHG reduction target by 2030, the targets in RE&EE plans must be at least 50% and 75%, respectively.

3.4. Conclusions

There are different approaches for the classification of models, and this study selects the traditional scheme. This means that it classifies them into two types: Bottom-up and Top-down (technical and macroeconomic models, respectively). It defines the procedural framework for the hybridization based upon these two types of models. Models' hybridization is not a new discussion, so the authors recognize the importance of structuring a model that allows complementarity between them, taking advantage of the virtues of each one. It means to use the quality of technical information along with macroeconomic evaluations. There are also utopian models used as a reference that allows evaluating all the edges of microeconomic, macroeconomic, and technological analysis.

There are several alternative models, but, considering the goals of this study, we considered the use of the LEAP model for energy-environmental prospects as the most appropriate alternative. As shown, this model is appropriate both for developing economies, and for evaluating productive transition and environmental aspects. Besides, there are several macroeconomic modeling alternatives. We chose the GEM because it allows for determining the behavior of economic sectors and consumers, based upon the price variation of products and services. This is an important criterion, as it links technical and economic models.

Based on the previous studies of hybridization models[8], we found two key factors in the process. First, the definition of linking variables between the models, in which the variables that are responses for one model are also, at the same time, input information for the other process. Generally speaking processes related to energy aspects and production aspects demand for economic models. The second key factor in hybridization is the definition of the measuring point, which are the user-controlled variables to execute the iterations between models until its convergence. Generally, these variables have an energy-economic relationship, such as electrical or fuel prices, investment or production costs. The aim of the iteration process is the convergence of linking variables, followed by a comparison with the response of independent models to determine its degree of contribution to the analysis.

This study proposes the hybridization between the LEAP model (bottom-up) and the General Equilibrium Model (top-down). This means a model hybridization of a technology base with a macroeconomic model. Both will be applied to the Ecuadorian conditions, aiming to assess the impacts of the NDC's implementation. We selected a soft-link approach between these two models. Hard-link and integrated stages are desirable, but it implies greater use of technological resources and information, conditions that are not within the scope of this study. We leave the debate open for future contributions or further development of this research area.

4. Methodology

This research proposes an innovative methodology to address and determine the socio-economic impacts of the NDC's implementation using a hybrid model. The hybridization of button-up with top-down models allows us to evaluate specific aspects based upon the prestige of technical models. It also addresses different aspects of

[8] For example: MESSAGE-MACRO, MARKAL – MACRO, and GEM-E3T.

society through macroeconomic models (Figure 6). This proposal contributes to future hybridizations studies, including a hard-link approach or full integration of these models.

The use of the LEAP model is justified by its versatility and its focus on environmental aspects. Besides, it is also regarded as a technical model (bottom-up), which allows us to establish a productive structure of a society with better precision. The CGE is the most appropriate top-down model to determine macroeconomic implications that results from existing policies or conditions in society. It also determines the behavior of economic actors. In this context, this study proposes the creation of a hybrid model between LEAP and CGE, named Central Planning Model energy-environmental-economy (MPC3e), which is developed in the Ecuadorian economic-energy conditions to evaluate the implications of environmental policies.

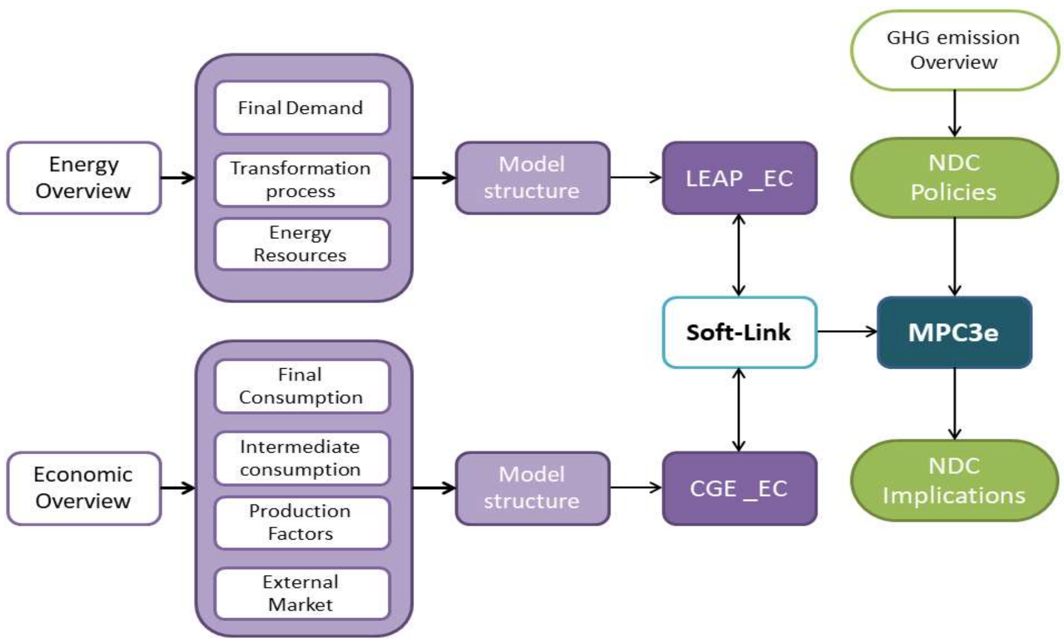


Figure 14 Modeling framework of this thesis

Before hybridizing the models, we need to develop each one independently. In other words, it is required to develop a LEAP model and GEM model applied to Ecuador, considering the technological conditions and productive structure of the country in them. This chapter has three sections. The first present an overview of the energy context of Ecuador and the structure of a LEAP model applied to the country, called

LEAP_EC. The second section presents an overview of the economic and productive conditions of Ecuadorian society and the development of a computable general equilibrium model, called CGE_EC (*Figure 14 Modeling framework of this thesis*Figure 14). The last section presents the hybridization process between both models, obtaining the MPC3e model. This section also explores the premises for hybridization, the exogenous and endogenous variables for each of the models, the data used and the process of convergence.

4.1. LEAP_EC model

In this section, we present the structure of the LEAP model applied to Ecuador. Due to its modular structure (energy chain), we present it in its disaggregated form, according to the main components of the energy-environmental chain. These are Final Demand, Transformation sector, and Energy resources. For each component, we analyze the operational features and point out which specific premises are assumed.

4.1.1. About the Ecuadorian energy sector

Crude oil production in Ecuador began in the 1970s. Since then, it became the most exploited source of energy in the country. This resulted in changes both in the economic structure and in the territorial urban organization CEDIG (1987). Production and export of crude oil became the main source of wealth generation; it reduced the role of other commodities in the economy, such as plantain and cocoa. In 2019, crude oil production has a share of 87.32% of primary energy production. This means a production of 195 million barrels annually, whose 70.33% are exported (Figure 15a). The revenues from crude oil sales had a share of 32.57% of the total exports BCE (2021). As Ecuador's economy depends on commodities such as crude oil, it has a highly vulnerability to external factors. This situation is worsened by difficulties in the local dollarized economy, responsible for decreasing the government's ability to define monetary policies.

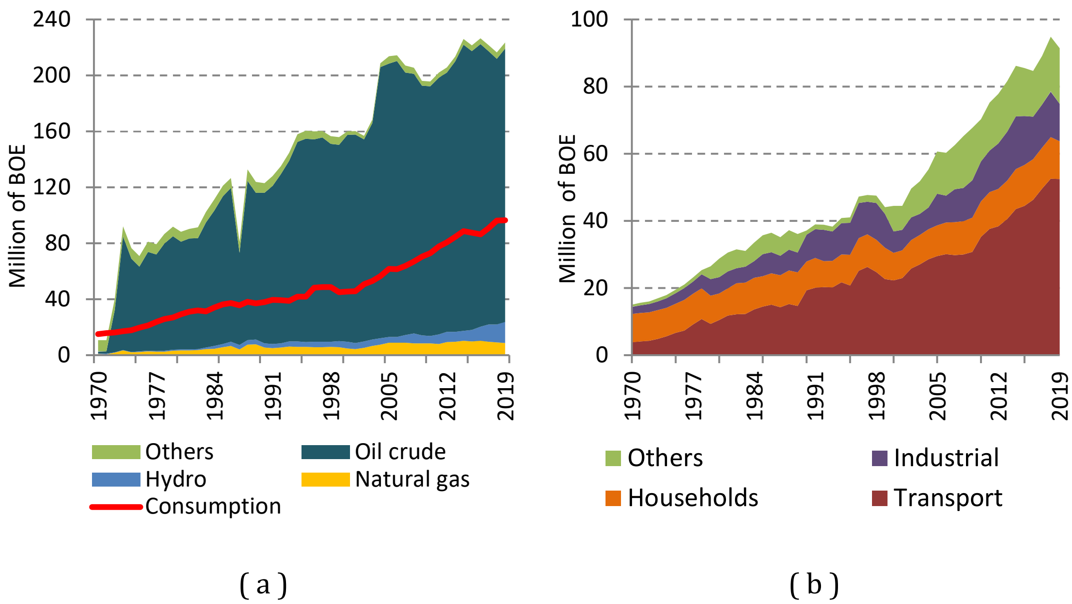
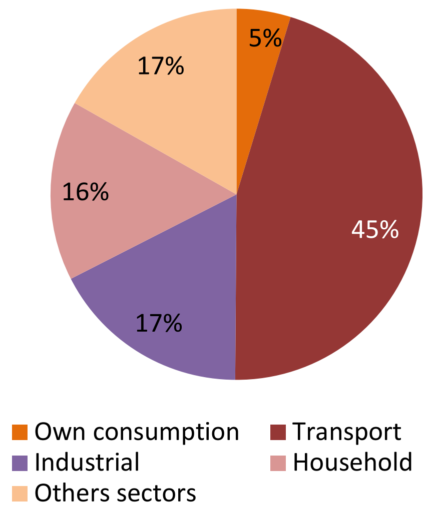
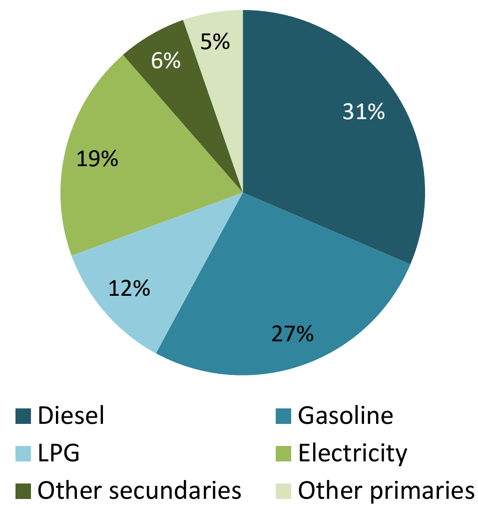


Figure 15 Evolution of energy production (a) and final consumption (b)
Source: OLADE (2022)

The Ecuadorian growth rate of energy consumption was 3.37% between 2008-2019 (Figure 15b), the main energy consumer is the transportation sector, which has gradually increased its consumption in recent years. In the 1990s, it reached its peak value of above 50% OLADE (2022). The fast economic-energy growth, together with a limited refining capacity (currently 176 thousand B/D) and a deficit of locally produced oil products opened a gap between supply and demand of local domestic fuels. This resulted in significant imports of gasoline, diesel, and LPG, the equivalent of 67.5% of the volume of domestic consumption. From an economic point of view, it implies significant investments in oil product imports. In 2020, Ecuador's final energy consumption was 96 million of BOE, and CO_2 emissions were 34 million tons. Transportation and power-generation sectors had a share of 48.5% and 14.6%, respectively. Besides, 73.8% of the total GHG emissions were related to diesel, gasoline, and fuel oil consumption. The former two were mainly related to the transportation sector.



(a)



(b)

Figure 16 Final energy consumption by sector (a) and source (b)
Source: MERNNR (2021)

The residential sector had a consumption of 13 million of BOE, and the majority consumption of LPG was intended for cooking. Electricity consumption is mainly destined to electrical appliances, in which air-conditioning has increased its consumption in the last five years Porras (2020). It is important to mention that LPG is subsidized in the Ecuadorian market and the sale price is fixed in the final market at USD$ 1.6 for 15 kg packaging. However, prices in Peru are USD$ 23.25 for 15 kg, and in Colombia US$17.00 for 15 kg. Due to the difference in prices, there is a lot of contraband at the borders. The industry sector has a greater diversity of energy sources, but its consumption has a low contribution in the total consumption due to the low-level industrialization of the Ecuadorian economy. Other sectors have a share of 17% in final consumption and include commerce, construction, and agriculture.

There are four kinds of transformation centers: refineries, power stations, gas centers, and distilleries. The former two are responsible processing 91% of the primary energy. A gas center is destined for its consumption and a distillery for ethanol production. On the refineries, the nominal refining capacity is 175 Bbl./day. In Ecuador has three main refineries: Esmeraldas (65%), La Libertad (25%), and Shushufindi (10%). Although the country has transformation capacity, it is not enough to supply the total market and implies a significant import of fossil fuels.

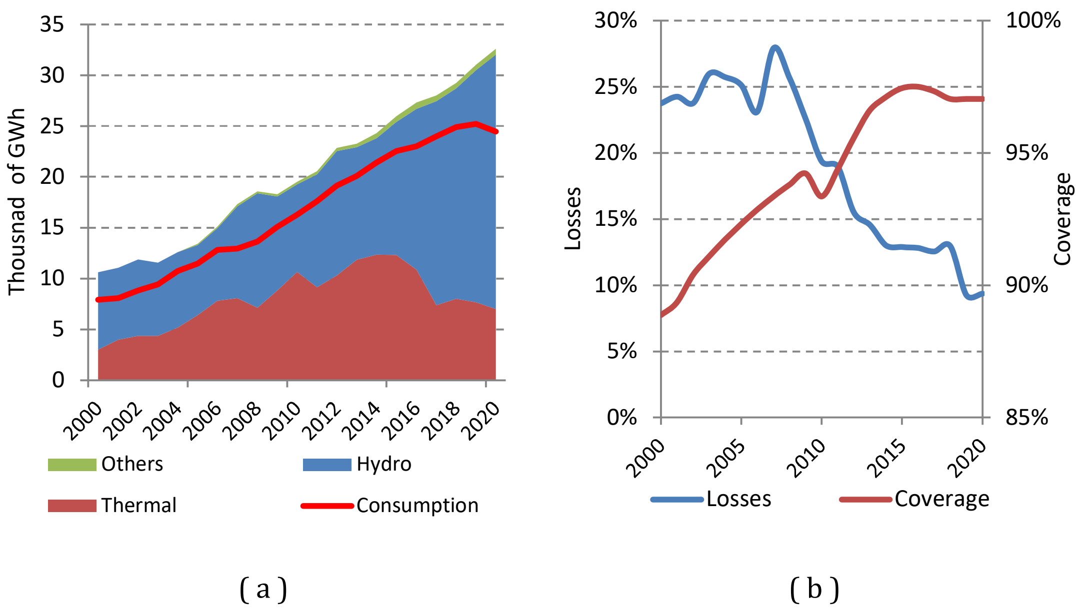


Figure 17 Evolution of electrical generation (a) and electrical index (b)
Source: OLADE (2022)

There are two main types of power stations: hydropower and thermal power. Over time, several hydroelectric projects have been constructed (Figure 17a). The nominal power generation almost doubled its value between 2008 and 2020 (from 4,544 MW to 8,712 MW). In 2020, the installed capacity existing in Ecuador had a 58% share of hydroelectric plants, 39% of thermal plants, and the remaining 3% is distributed among non-conventional renewables energies. Thermal power plants are based on natural gas, biomass, and fuel oil consumption. The government's electricity generation expansion plan prioritizes the use of natural gas in power generation, so oil consumption has been significantly reduced in recent years. Biomass consumption is used to power stations in sugar mills, by producing energy for its own consumption. Losses are characterized in two types: transmission and distribution. Between 2008 and 2020, the distribution losses decreased from 19.6% to 12.79%, while transmission losses have decreased from 9.8% to 4.55%. This is due to significant investments in the electrical sector (Figure 17b).

Oil is the main energy source and the main source of income for Ecuador, and this depends on government policies. Even though the production and consumption of hydrocarbons is depended on market conditions. In 2016, the oil reserves were estimated at 4,160 million Bbl. They were linked to an annual production of 190 million

Bbl. MERNNR (2017). Natural gas reserves are not significant and are used to power generation. On renewables sources, there are significant reserves of biomass and hydropower potential, but its investment levels are restricted.

4.1.2. The LEAP applied to Ecuador – LEAP_EC

The LEAP_EC considers economic, demographic, and technological aspects of the country being studied. They are defined as key assumptions, so the final energy consumption depends on GDP and population growth, along with energy intensity for each demand group and sector (Figure 18). The model uses a bottom-up approach to determine the energy consumption of several sectors and considers the interrelation among them, including competition of all sectors to obtain energy.

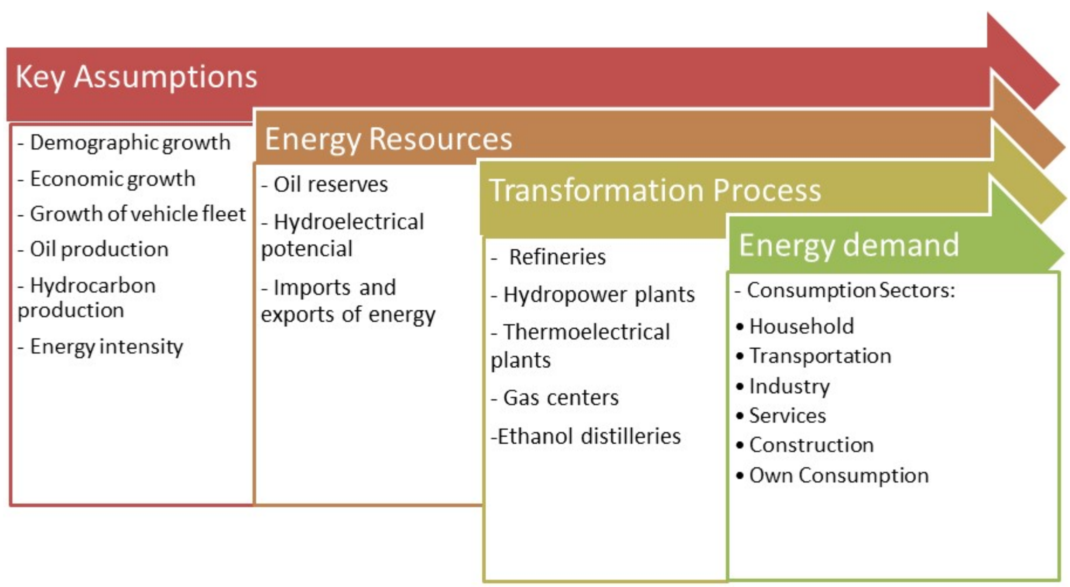


Figure 18 Modeling framework of LEAP_EC

The final energy demand is satisfied by the transformation process output, including the transformation process by availability of energy resources, mainly oil reserves and hydro energy. Energy demand considers all consumption sectors in society and the transformation process considers all available infrastructures, along with expansion plans, and the interaction between primary energy production and external and domestic markets.

Final Demand

The final energy demand is the sum of energy demands for each sector. As it considers the various behaviors and dynamics of the sectors, the LEAP_EC uses two modeling structures for the final energy consumption: a parametric and econometric. The former is used to determine the consumption in sectors with high technology dependence. The latter is used for other sectors, which have a high correlation with economic growth. The Equation *1* represents the aggregate calculation.

Final Energy consumption:

$$CE = \sum_{j=1}^{n}\sum_{i=1}^{n} E_{ij} \cdot \omega_{ij} + \sum_{k=1}^{n} f(x)_k \qquad \text{Eq. } 1$$

Household and transportation sectors have a parametric logic, represented in the first terms of the equation 1. The energy consumption in each sector is the product of the unit consumed of each element (ω_{ij}) multiplied by the total number of elements in each level (E_{ij}). These levels are composed of several divisions, according to social and technological aspects, end uses, and energy sources. The industrial, commercial, construction, and other sectors have an economic/energy relationship according to their historical trends and growth perspectives, using an econometric function, represented in the last term of the equation 1.

Final Energy consumption by sector:

$$CE = \sum_{i=1}^{n=12} E_{i1} \cdot \omega_{i1} + \sum_{i=1}^{n=14} E_{i2} \cdot \omega_{i2} + \sum_{i=1}^{n=23} E_{i3} \cdot \omega_{i3} + \sum_{k=1}^{3} f(GDP)_k \qquad \text{Eq. } 2$$

The equation 2 represents the calculations by each sector, where the three first terms represent the consumption in household and transportation (including both cargo and passengers) sectors, respectively. The last term is a function of the economic growth represented by the variation of the gross domestic product (GDP).

In the residential sector, this study considers a parametric scheme proposed by Kumar, Bhattacharya, and Pham (2003). They structure a LEAP for households in Vietnam with three levels from geographic to technological disaggregation. A similar scheme is used, but with four levels of disaggregation for all households, considering an electricity access level to represent the Ecuadorian reality in this study. The first level of desegregation is population location, which is divided into urban and rural areas. In Ecuador, there are a significant number of households in rural areas, and these households have a different "energy-consumption behavior" when compared to urban households. This is due to lifestyle, cultural, and geographical aspects.

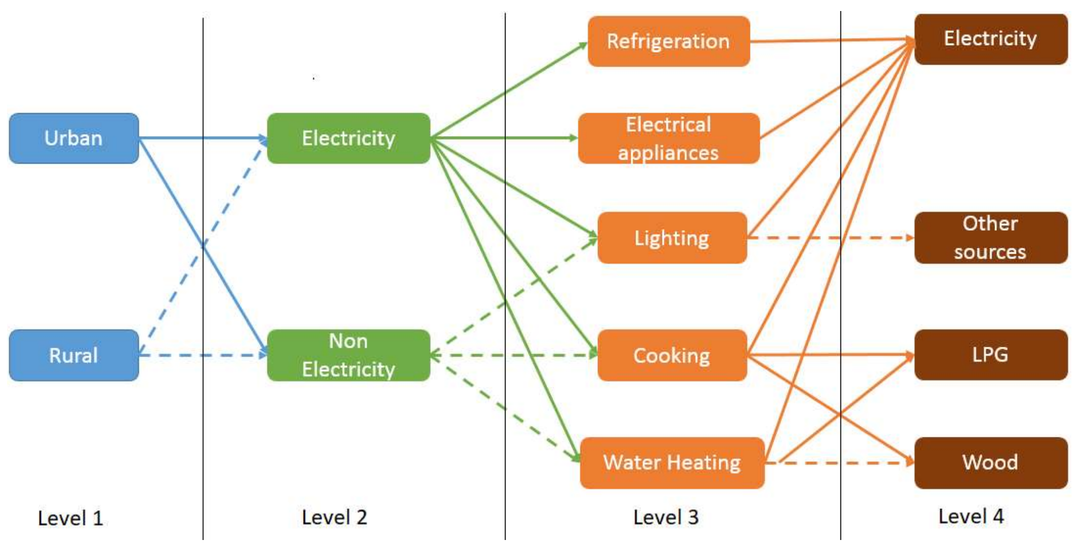


Figure 19 Modeling framework in the household sector

The second level accounts for electricity access. In recent years, the number of households with electricity has risen, which implies an increase in electrical consumption. The third level considers the end-uses and the type of technology used to evaluate the main energy uses in households and government energy efficiency programs. The last level is related to the type of energy sources and it demonstrates the competition between residential areas and other sectors for the existing available energy sources. The basic unit to determine total energy consumption is the number of households by division until level 4 (Figure 19).

The transportation sector includes all existing modalities: maritime, air, and land. Among these modalities, land transportation is the most dynamic and the main energy consumer. The correlation created determines the annual energy consumption in maritime and air transportation. This correlation shows fuel consumption to fleets of ships and aircraft. One might consider the growth of maritime ships and aircrafts based on historical data that shows its energy consumption. Concerning land transportation, a parametric model is structured to determine the annual energy consumption. This parametric model considers 3 variables: number of vehicles, performance, and the annual distance traveled. The number of vehicles is established by the historical data of vehicle fleet in Ecuador, available from the statistics institute. This data is arranged in 5 disaggregation levels according to the type of use, intensity, vehicle, engine, and fuel, as seen in Figure 20 and Figure 21.

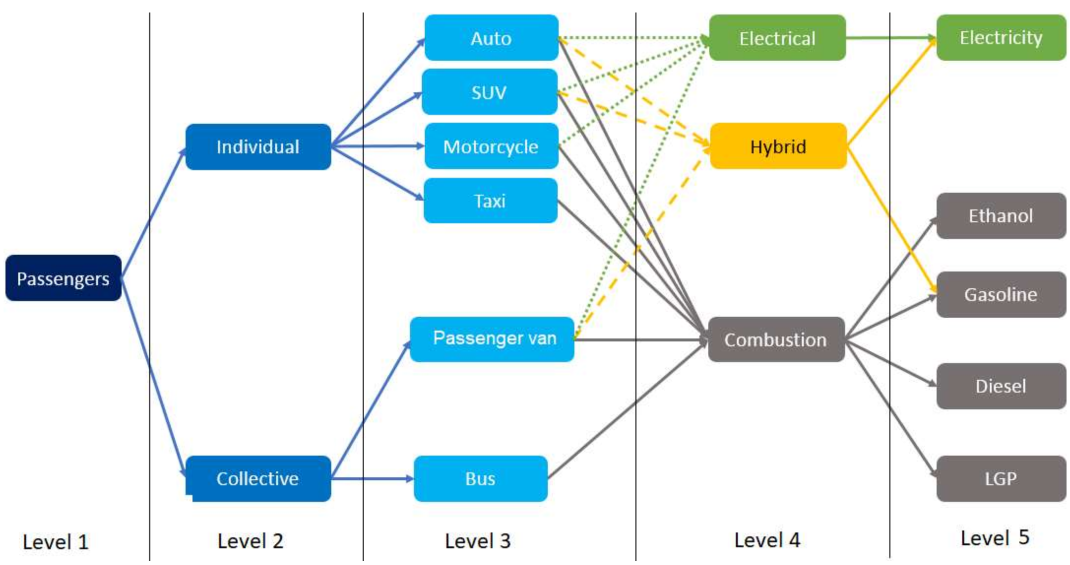


Figure 20 Modeling framework in passenger transportation sector

The first disaggregation level corresponds to the vehicles' type of use (passengers or cargo), as they have completely different practices and behaviors. Passenger consumption is correlated to demographic parameters, while cargo consumption is related to economic ones. The second disaggregation level corresponds to the types of vehicles (individual or collective transportation). Individual transportation includes Auto, SUV, Motorcycle, and taxi. Every type has a different focus of use and consumption. Collective transportation has two types (Bus and VAN). A bus is a large transportation type, used for city and intercity transportation. Vans are majorly used for tourism and school.

The fourth level refers to the energy source feeding the vehicle: electrical, hybrid, and bio/fossil fuels. Internal combustion engines are the largest share, so the fleet of electric and hybrid vehicles has a minimum share in passenger consumption. The model considers the penetration of both technologies. The last level is related to fuel type, the largest energy consumption being related to oil products, mainly diesel and gasoline. The model also considers ethanol use to evaluate its penetration rate in the domestic market. This level shows the tradeoff competition between technologies, as well as the impact of energy efficiency policies (Figure 20).

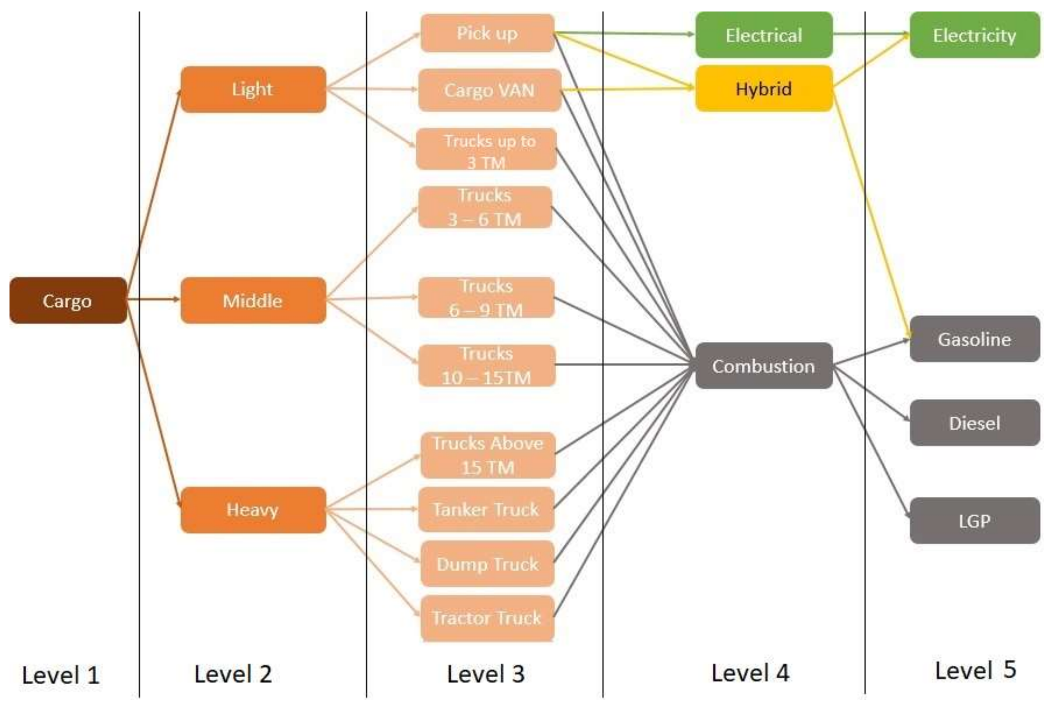


Figure 21 Modeling framework in cargo transportation sector

Cargo vehicles are arranged according to their load capacity: light, medium, and heavy. The third level considers cargo dimensions and uses aiming to identify the main consumer to structure specific policies (Figure 21). Regarding passenger transportation, the internal combustion engine is the most common at the fourth level. The fifth level refers to fuel type, in which diesel covers almost the entire demand, due to the large demand for diesel engines in the cargo fleet.

In other sectors, there is a positive correlation between wealth generation and energy consumption for all productive sectors. Therefore, we consider an economic-energetic energy consumption estimate by sector, using the historical relationship between the growths of GDP values and their respective energy consumptions (Table 4). This means that a high economic growth implies a high energy consumption.

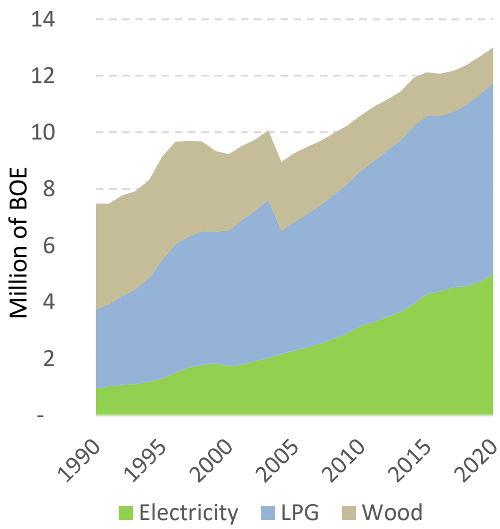
Table 4 Economic Relationship - Energy by sector

Sector	Correlation (GDP– Energy Consumption)
Industrial	0.80
Agriculture	0.75
Commerce	0.98

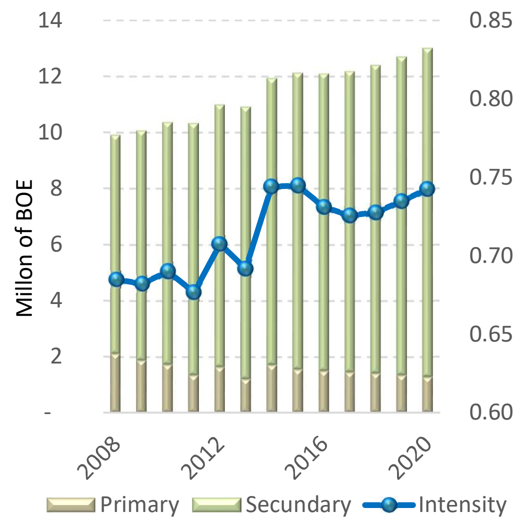
Even though the industrial sector is the second-largest energy consumer, its GDP contribution is low (the equivalent of 13%). This is probably due to the low level of industrialization in Ecuador, which means that industries with high energy consumption have low wealth generation. The commercial and service sectors are the main GDP contributors (at around 43% in total).

We introduced the information that allows us to estimate better the final energy demand, along with different characteristics that allow us to obtain a model that is as realistic as possible. As the NDC considers 2010 as the base year for the Energy, Agriculture, Industrial Processes, and Waste sectors, this study will do the same, guaranteeing comparability. The number of households for each division is referenced by information from INEC (2010a). This was obtained from the 2010 national census, which stated the existence of 3.9 million households with an average of 3.78 inhabitants per household (64.02% urban and 35.98% rural). Where, 97.77% of urban households and 89.59% of rural households have access to electricity.

In general, the urban population has a greater number of household equipment, including refrigerators, spotlights, kitchens, air-conditioners, televisions, and cellphones. For consumption divisions in the model's last levels, we use a historic trend based on national energy balances, along with projections of population growth INEC (2010b).



(a)[9]



(b)

Figure 22 Energy consumption in households by source (a) and intensity (b)
Source: MERNNR (2021)

Households' energy consumption has been gradually increasing at an annual growth rate of 2.25% in the last decade (Figure 22a). The consumption of firewood decreases over time due to greater penetration of LPG and electricity. The model considers different energy intensities for different types of technologies and their historical behaviors. For cooking activities, there are three different intensities defined per house-month: LPG stove with 12 Kg of LPG, wood stove with 2.7 m^3 of wood, and electric stove with 68 kWh (Figure 22b). The amounts of each type were determined by energy balance and official reports. According to the statistical institute in 2010, the average number of light bulbs per household in the urban area is 4.81 low-consumption lamps and 1.71 incandescent lamps, while in the rural area it is 3.25 low-consumption lamps and 1.75 incandescent lamps per home. These values will change throughout the model to reach current conditions, as there is a growing number of LED lamps in homes.

The efficient cooking program is the only initiative for the residential area proposed in the NDC unconditional scenario (Table 2). This initiative refers to the PEC Program, which aims at replacing the use of LPG with electricity for cooking and water heating. This should be achieved by replacing LPG for induction stoves in 3 million households. Besides, they also consider the use of electrical equipment for water heating

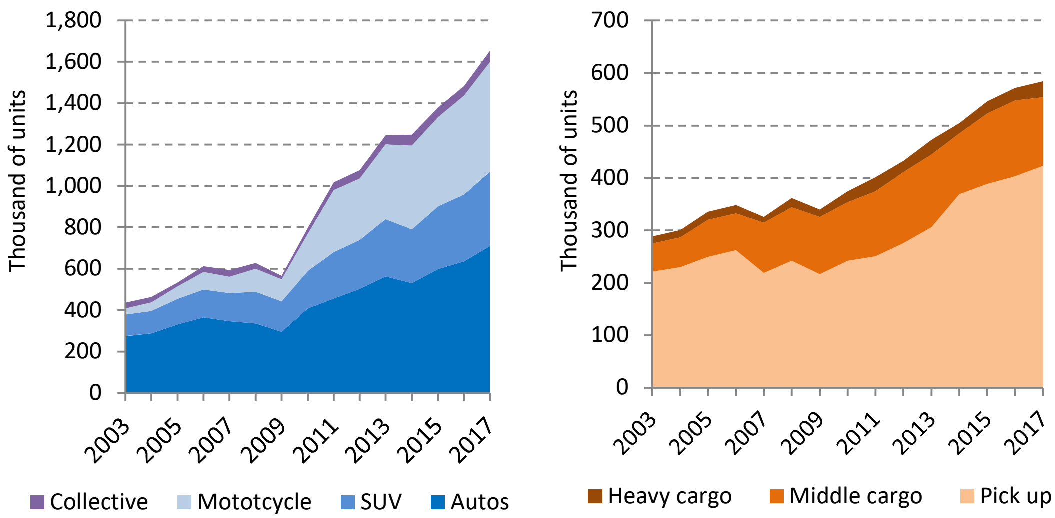
[9] Due to marginal consumption of Natural Gas in households, it is not presented in the Figure 22a

for 750.000 homes. However, the PEC program is under evaluation because the incentive conferred by the State to customers ended in 2018. Besides, the total number of kitchens sold did not exceed 800.000 MEER (2017a). This indicates that it was not possible to meet the goal set by the Government, since sales represented approximately 25% of the expected.

The initiatives for the residential sector in the NDC conditional scenario refer to the Energy Efficiency Plan. Its main objective is to strengthen programs for replacing electrical appliances and other equipment with high energy consumption for low-consumption ones. It comprises three action lines: end-use energy project, standardization, equipment labeling program, and replacement of equipment with high energy consumption. If these initiatives worked as planned, the total savings would be 88.000 BOE by 2035.

Regarding the transport sector, fuel consumption of ships and aircraft is related to fleet growth. We consider that there is a growth of 2% of maritime ships and 5% of aircraft happening every ten years, based on historical data over the past 20 years. It is important to notice that land transport has a 94% share of all fuel consumption in this sector MERNNR (2018a). The model structure has significant levels of disaggregation (Figure 20 and Figure 21), using annual vehicle statistics. These are very reliable because all the vehicles circulating must pass an annual check at the country's Traffic Agencies. Hence, the annual vehicle fleet is the reflection of vehicles circulating in the country. Even though there are cases of not registered vehicles, but this is a minority group.

Figure 23 shows passenger and cargo vehicles increasing significantly in the last years. The annual growth rates for the last decade were 10.77% and 6.02%, respectively. Based on Ecuadorian historical data, 723 thousand vehicles circulated in 2003, and this number tripled in 2017, to 2.23 million vehicles circulated.



(a) (b)

Figure 23 Vehicle fleet evolution (a) passengers and (b) cargo

Source: INEC (2018)

To determine energy consumption, the model considers performance and annual distance traveled in each division. This is based on previous studies conducted by INER (2012) and Sierra (2016), for the Ecuadorian case. Both studies obtained the following parameters: Vehicle kilometers traveled - VTK and energy performance for the divisions in each level. These values are multiplied by the number of units in each level, resulting in the energy consumption by division. Regarding vehicle trends per division, the model proposes a relationship between fleet size and GDP growth, as proposed by Castro, (2017).

Ecuador has no significant participation in any rail transport mode. However, efficient public transport is the only initiative in the NDC unconditional scenario for the transport sector. Therefore, the Tramway in Cuenca and the Subway Line in Quito are considered in the model, as they began operations in 2019 and 2020, respectively. It is important to state that the NDC unconditional scenario does not propose any action line for cargo land transport, even though this category concentrating 67% of energy consumption MERNNR (2018a).

The trends of increasing local electricity generation, along with a worldwide increase in electric transportation may favor the expansion of an electric vehicle fleet in the domestic market. It implies a technology change based on the wide availability of hydropower. Regarding ethanol use, it is mainly consumed in coastal cities, so, due to technological transition possibility, the model uses gasoline and ethanol as substitute products.

The industrial sector has always been on the governments' agendas to change from a primary exporting economy to an industrialized one. There are additional governments' proposals, including cellulose and paper, aluminum manufacturing, copper industry, petrochemicals, and shipyards. However, they are not considered in this model, as they are still at an early stage of development. We desire a parametric structure that considers energy consumption per unit produced or per production capacity. However, due to the limited information on this sector, along with the low presence of energy-intensive industries (Table 4), this model uses an energy-economy equation to estimate energy consumption in this sector (Table 5).

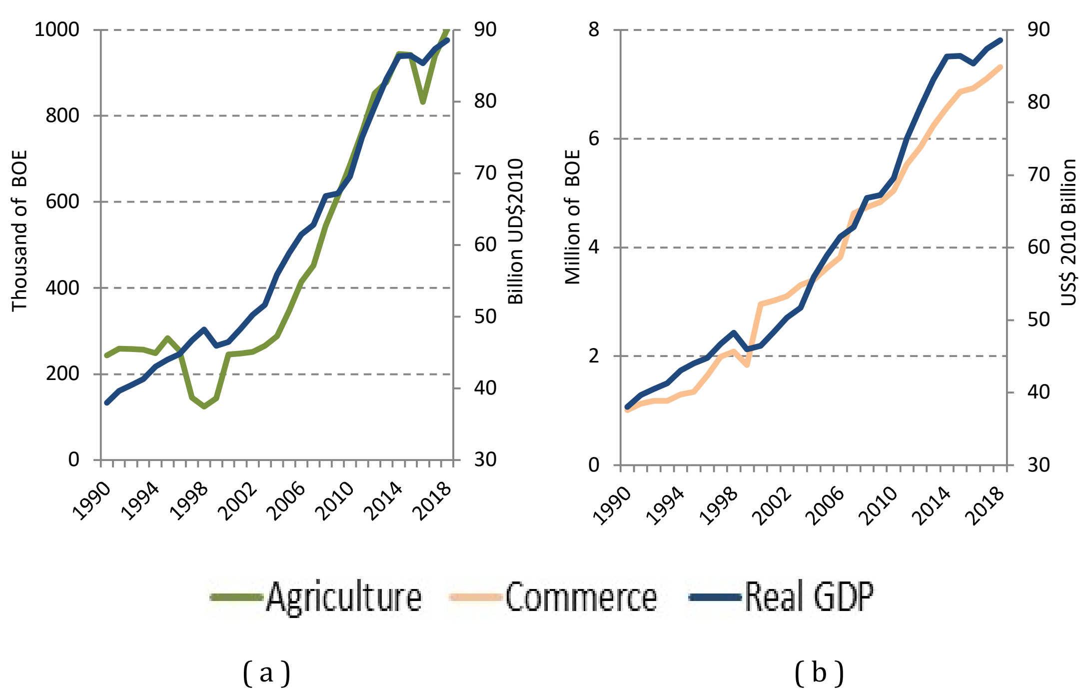


Figure 24 Energy-economic relationship: (a) agriculture and (b) commerce
Source: Prepared with data from OLADE (2022)

The information presented in Table 4 is based on historical data (from 1990 to 2018) available at OLADE (2022). The GDP has a high level of relationship with the energy consumption by sector. Figure 24 shows that energy consumption in agriculture and commerce have almost the same tendencies as GDP growth.

Table 5 Energy-economic equations by sector

Sector	Equation[10]	R^2
Industrial	-199 + 0.1652*GDP	0,72
Agriculture	-639 + 0.01837*GDP	0,94
Commerce	-3485 + 0.1209*GDP	0,98

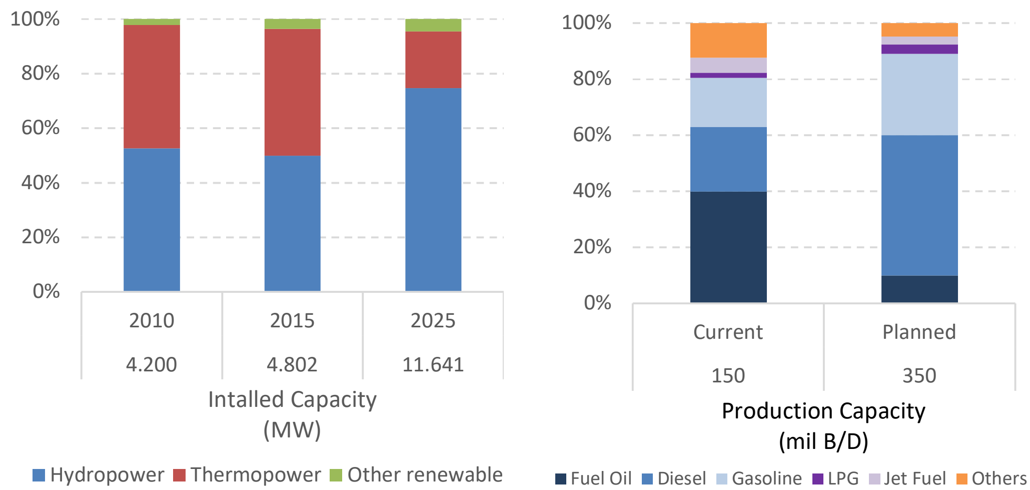
Table 5 presents equations and determination coefficients to estimate energy consummation. Agriculture and commerce have high levels of significance and it means that the predictions are proximate to the real data. Thus, the regression is applicable to estimate energy consumption and the same logic is used for other sectors, representing 10% of final energy consumption. The industrial sector has an intermediate level of significance in energy consumption, despite its role in wealth generation.

Transformation sector

This study considers the physical infrastructure available in the country in 2018: three main oil refineries, hydroelectric plants, thermoelectric plants, and a gas processing center. We obtained complementary information (nominal capacities, processing, supply and production, and expansion planning) from official sources and local energy companies MERNNR (2018b). To forecast the industrial energy consumption, we considered the execution of Pacific Refinery project. The reason for this is that there is not a specific industrial expansion plan in Ecuador.

[10] GDP is quantified in millions of USD

The model prioritizes two energy policies: the increase in hydroelectric infrastructure and the change in the refining structure. Figure 25 presents projections for both policies, according to the official information available from ARCONEL (2016) and MERNNR (2013). The first policy consists of constructing large hydroelectric power plants, which will be gradually incorporated into the national system. This means an increase of 6,296 MW in installed power capacity by 2025. In addition, the Ecuadorian power expansion plan considers the Santiago hydropower[11] project to be completed by 2023. It entails the inclusion of 2,400 MW of installed capacity to the grid and will be considered in the NDC conditional scenario due to its high investment levels.



(a) (b)

Figure 25 Transformation trends: (a) generation power and (b) refining structure

Increasing the hydropower capacity implies a reduction in thermopower generation, and - in turn - GHG reduction. Consequently, it creates an increased availability of fuels that were destined for electric energy production. An interesting answer is to determine the behavior of all sectors by considering this resource availability.

[11] The project will be located at the confluence of the Zamora and Namangoza rivers (Santiago river), where the Cordilleras del Cóndor and Cutucú meet, in Morona Santiago province, Ecuador.

The second energy policy consists of constructing a new refinery (the Pacific Refinery) with a capacity of 300 thousand barrels per day. This project was a priority in Ecuador, due to the significant import amount of oil products. This refinery would bring a change in the energy matrix, allowing for positive impacts on society, such as an increase in GDP, import reduction, and a decrease of the unemployment rate (Castro, Graßmann and Cunha, 2018). The model only considers the execution of the first stage, beginning in 2021.

Energy resources

Ecuador's proven oil reserves are 4.1 billion Bbl., and it is linked to a production of 500 thousand barrels per day MERNNR (2017). This means that, at the current consumption and exportation rate, there are 38 years of self-sustainable oil consumption, an unfavorable horizon. Implementing the Pacific Refinery implies a reduction in crude oil exportation in favor of domestic refinery supply. As the Ecuadorian economy depends on exporting commodities such as crude oil, the economy becomes highly vulnerable to external factors (Correa, 2005). We expect market responses related to oil product imports, increased availability of energy resources for exportation, and a dispute between different sectors for these available resources. Another alternative is to increase the capacity of crude oil production to maintain oil exportation income. However, this alternative is not considered in this model, because there are no significant new reserves to be explored in the long-term.

Natural gas is another available resource in Ecuador, but on a smaller scale than crude oil. Proven natural gas reserves in 2015 were 11.10 Gm^3, linked to an annual production of 1.68 Gm^3. This hydrocarbon is primarily destined for energy generation. This scarce reserve has favored non-intensive natural gas use in final consumption. Nevertheless, power generation expansion plans to incorporate 180MW by using thermal power plants fueled by natural gas.

According to Arconel (2014), Ecuador has 11 hydrographic systems with a potential of 73,390 MW, and 21,520 MW is economically feasible. Expansion plans include using 31.77% of the economically feasible potential. There is an expected increase in electrical energy available to satisfy the internal demand, releasing the remaining available amount for regional exportation.

On non-traditional renewable resources, there are currently two wind farms in the Galapagos and Loja provinces, with a total nominal capacity of 21 MW. However, according to the Ecuador wind atlas, there is a wind potential of 1,691 MW for electrical generation. There are also 21 photovoltaic power plants, with a total nominal capacity of 26 MW. These are mainly focused on the Galapagos Islands to create a clean region, with an entirely renewable electric generation matrix. Biomass is used for electricity generation and ethanol production. Biomass-based electricity generation is destined for local sugar cane industries, and there is an installed capacity of 134 MW.

4.2. CGE_EC model

In this section, we present a Computable General Equilibrium model applied to Ecuador (CGE_EC). It is worth mentioning that - within its limitations - there is a high level of aggregation, with a restricted integration of information from primary and secondary sources. This limitation has been overcome by hybridizing a technical model. The first section presents a brief overview of the Ecuadorian economy to put in context the CGE structure, the second section presents the equations that govern the model. The CGE_EC's approach assesses the implications of NDC, along with the conditions for hybridization with the LEAP model.

4.2.1. About the Ecuadorian economy

GDP growth is the main indicator of development in the traditional economic scheme. We define it as the main variable of interest within the CGE_EC, including its variation over time. The country's contemporary economic history could be summarized in three periods: oil Boom, pre-dollarization, and post-dollarization. In the 1970s, Ecuador began to produce oil and it became the largest source of primary energy available in the country. It implied structural changes in the Ecuadorian economy and this period is called by economists the Oil Boom Acosta (2006). From the 1970s until at least 2022, the Ecuadorian economy depends on oil production.

Table 6 GDP growth historical evolution

Classification	Range	GDP growth
Oil Boom	1966 - 1980	5.8%
Pre-dollarization	1981 – 1999	2.4%
Dollarization	2000 - 2017	3.7%

Source: Prepared with data from BCE (2021)

Oil exports play an important role in the income of the Ecuadorian government and society. The greatest economic growths are tied to the Oil Boom, which reached 13.95% and 11.21% in the years 1973 and 1974, respectively. During this period, there was an increase in the planning capacity of the government due to the abundant economic resources. The Pre-dollarization period resulted in political instability. The most critical situation was in 1999 when the GDP rate was -4.73%. The dollarization of the Ecuadorian economy marks a breaking point in the country's economic history, which is the loss of monetary power due to dependence on foreign currency. From the Dollarization to current times, the country maintained an average growth rate of 3.7%. Variations were related to international oil prices falling, and natural catastrophes.

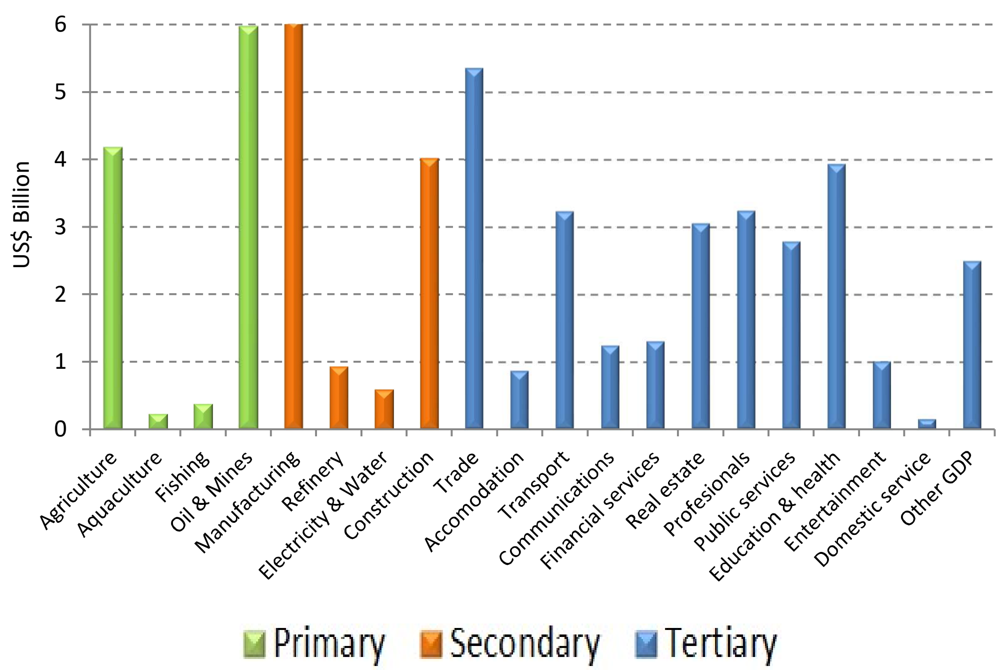


Figure 26 GDP disaggregation by sectors
Source: Prepared with data from BCE (2021)

Figure 26 shows that the GDP contribution of the manufacturing industry is equivalent to the contribution of the Oil and Mines sub-sector. The oil refining installed capacity has been gradually increasing, but the rapid energy consumption resulted in the domestic fuel production not being able to satisfy the domestic demand. This is an important characteristic when evaluating NDC energy scenarios. The primary and tertiary sectors have different behaviors in their GDP contribution. The former has a high concentration in a few sectors, while the latter has a greater concentration on GDP. The primary sector contributes two subsectors - agriculture and crude oil. The tertiary sector (services) has a relevant presence in 11 subsectors, in which the trade subsector makes the largest contribution. This is the most dynamic and the largest generator of wealth and employment. It is a challenge to structure productive transition policies, with less economic impacts.

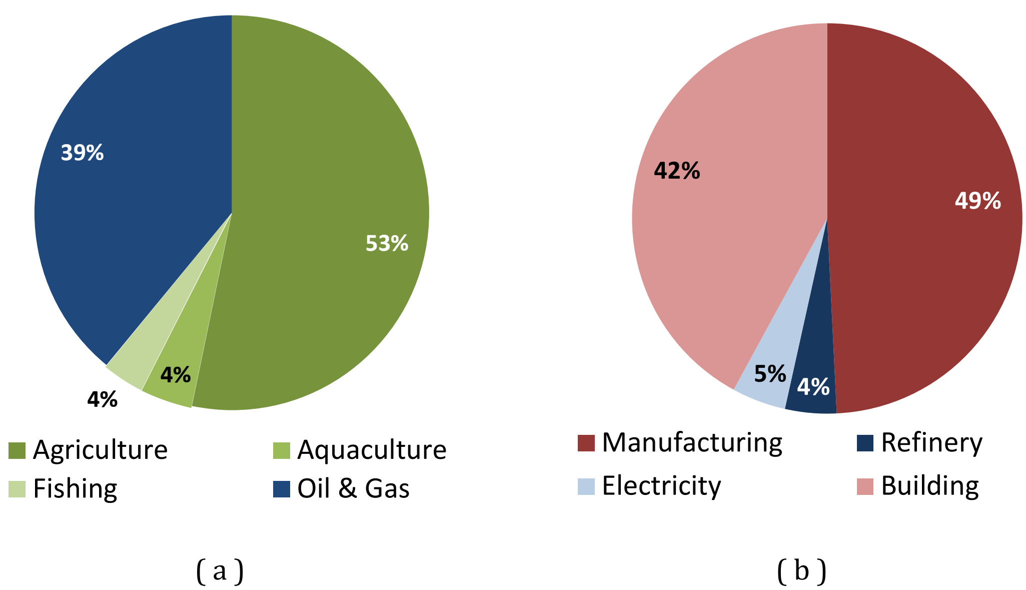


Figure 27 GDP disaggregation by sector (a) primary and (b) secondary
Source: Prepared with data from BCE (2021)

Figure 27a disaggregates the GDP contribution in subsectors. The agricultural and crude oil sectors have a share of 53% and 39% in the primary sector. It is a constant challenge for the governments to change the productive matrix. Energy sectors have low shares in the secondary sector. Oil refining and electricity have a 4% and 5% share, respectively. The manufacturing subsector corresponds to the major share, and the construction is an important contributor (Figure 27b). The dependence on crude oil exports results in an economy highly vulnerable to external factors. Despite the high prices of oil derivatives from 2009 to 2015, there was a negative trade balance. This demonstrates that if there are no high volumes of crude oil exports, there is a less favorable trade balance.

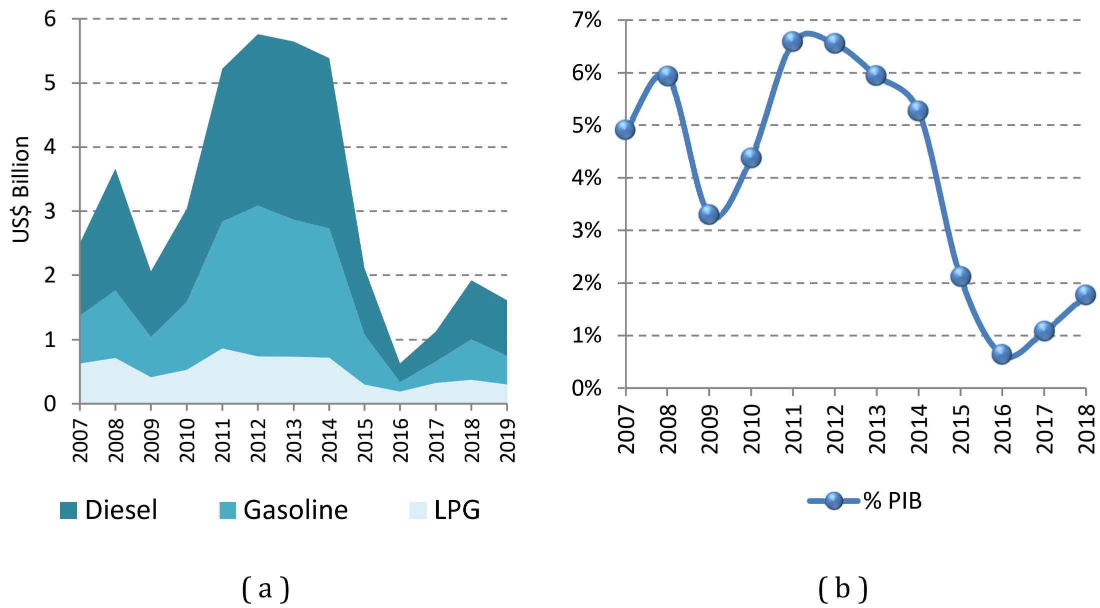


Figure 28 Subsidies historical evolution (a) oil products (b) GDP percentage
Source: Prepared with data from BCE (2021), Espinoza and Guayanlema (2017)

In terms of the NDC objectives and the country's oil economic reality, GHG reduction policies could be counterproductive to economic growth. This means that more than 60% of the final energy consumption matrix is related to the consumption of derivatives. The intention is to explore alternatives that achieve sustainable growth or at least minimize this impact. An opportunity that satisfies these conditions is related to the oil products imports due to the limited refining structure and rapid growth in consumption in the transport sector. It considers that Ecuador is a country that exports high volumes of primary resources to the world, such as crude oil and imports products with higher added value, such as oil products (Figure 28a). The situation is aggravated by the existence of high fuel subsidies, which has always represented a significant portion of GDP. It reached its peak in 2012 with US$5.7 billion, a value equivalent of 6.55% of GDP in nominal terms (Figure 28b). However, a significant reduction of it same is expected because of the new government policy, in which it defines price ranges according to international prices.

4.2.2. The CGE applied to Ecuador – CGE_EC

The CGE_EC is a computable general equilibrium model applied to the Ecuadorian economy. This is an algebraic framework based on the impositions of the axioms of producers and consumers for welfare maximization. The framework is based on previously contributions developed by Machado *et al.* (2021), Ribeiro and Cunha (2022). The current version is built upon the GTAP and the Ecuadorian Central Bank data base. To maintain consistency with the LEAP model and NDC conditions, the CGE_EC uses the social accounting matrix for 2010. This matrix structures the Ecuadorian economy into 25 sectors and the sectorial disaggregation is presented in Appendix A. Figure 26 also shows several of them.

Final and intermediate consumption

The final consumption is concentrated in the commerce and services sector (51%). In addition, there has been a stagnation of final consumption in the last five years (Figure 29). This is the opposite situation to the 2009-2013 whose growth was 9% per year. In the current period, the construction is the most affected sector with decreases in growth of 3% per year, accompanied by a reduction in the consumption of agricultural and manufactured products.

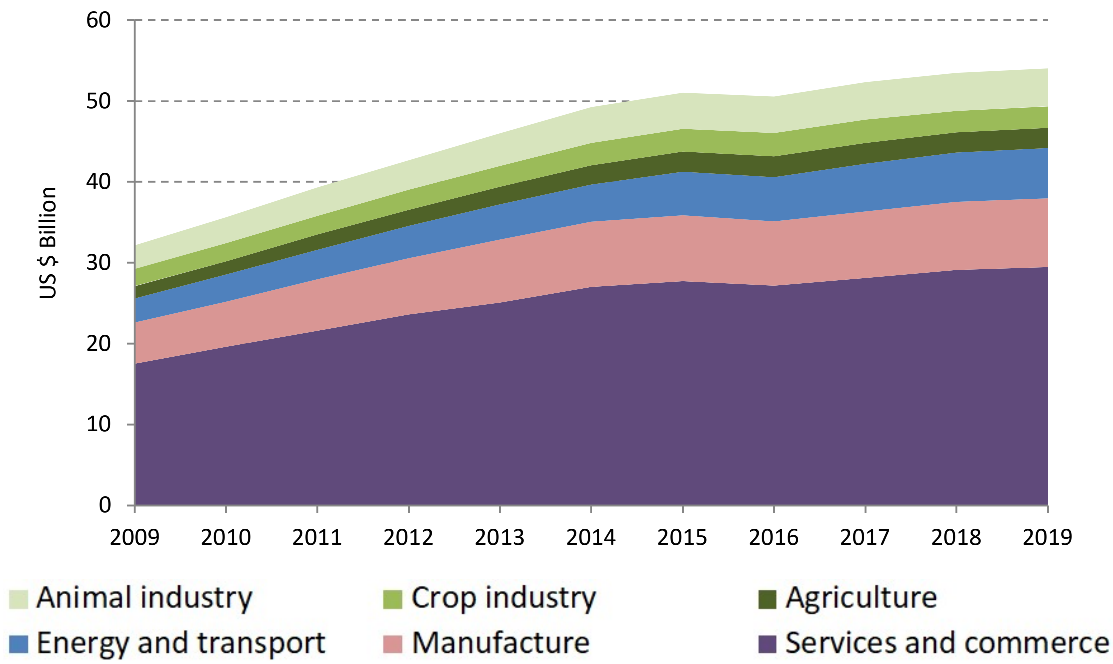


Figure 29 Final consumption by sectors
Source: Prepared with data from BCE (2021)

The manufacture, agriculture, and its industrial processes are the sectors with low variation and a sustained growth in final consumption. However, they have seen slight reductions during the last years. The energy and transportation sector has maintained constant growth and it is the only sector that has not faced reduced consumption due to vehicle fleets increase, an important feature to consider when developing a model. (Appendix Table A.4). The consumer behavior is defined as a LES function and it model considers minimum levels of subsistence per sector, which are linked to the budget constraint. The total level of subsistence is defined for the subsistence parameter (μ_{Hj}), taxes (tx_j), and price (P_j) by sector. The budget constraint for consumption is the difference between the available income of consumers (Y_f) and the level of subsistence.

Consumer behavior by sector:

$$C_i = \mu_{H_i} + \frac{\alpha_i}{tx_i \cdot p_i}\left(Y_f - \sum_{j=1}^{n} tx_j \cdot p_j \cdot \mu_{H_j}\right) \qquad \text{Eq. 3}$$

Equation 3 describes the consumption of goods and services. In it, *Ci* represents the amount of product *i* consumed, linking price (P_i), and consumption parameter (α_i). The equation also takes into consideration the subsistence parameter (μ_{Hi}). These parameters are important to consider consumer changes between sectors due to external conditions or incentive policies.

The intermediate consumption has a more equitable sectoral participation than the final consumption. The most representative sectors are manufacture and service, with 37% and 30% of intermediate consumption, respectively (Figure 30). The period between 2010-2013 had a significant increase of 9%. Nevertheless, in 2019, the intermediate consumption decreased 1%, this characteristic is present in most sectors and the worst affected one is the construction sector, which presented a reduction of 4% (Appendix Table A. 6).

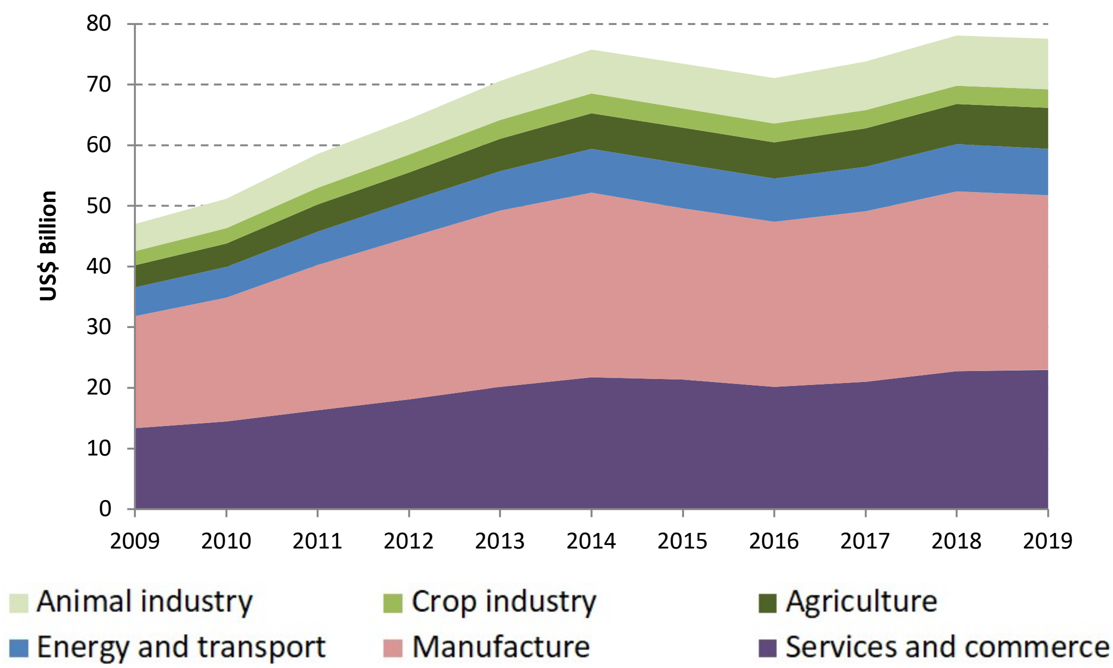


Figure 30 Intermediate consumption by sectors
Source: Prepared with data from BCE (2021)

Agriculture and animal industries, sectors which supply raw materials for the production chain, do not have significant variations. There are slight reductions in intermediate consumption, but not reductions. To determine the flows between inputs and outputs of the productive sectors, the model considers a Leontief structure ($\boldsymbol{L_i}$). This means that there is no sensitivity to the relative price variation between sectors. This characteristic could be considered a limitation to the model, but we proposed a Leontief structure in equation 4 due to the lack of specific information to structure other types of models.

Intermediate consumption:

$$\boldsymbol{Z_i} = \sum_{j=1}^{n} P_j \cdot q_{ij} \qquad \text{Eq. 4}$$

And

Intermediate technological parameter:

$$a_{ij} = \frac{X_i}{q_{ij}} \qquad \text{Eq. 5}$$

The total economic production for each sector (X_i) is represented by all intermediate consumption (q_{ij}) and all final consumption (C_i). The basic premise is a fixed demand/production ratio between sectors. The sector *j* input in the economy to carry out its production does not change and this relationship is represented by a technical coefficient (a_{ij}). This parameter is constant when the model was running. These coefficients are useful to evaluate technological changes due to environmental policies, which modify the productive structure of society.

Production factors

In 2019, the production remuneration was US$40 and 60 billion for labor and capital, respectively. In both cases, the service is the most important sector in the remuneration system (Figure 31). In it, the capital remuneration had an annual increase of US$127 million and it is the sector with the best capital and labor remuneration, which had an annual increase of US$866 million. The public sector is the second most important in the labor remuneration wit a share of 21%, as it represents the bureaucracy and public employees.

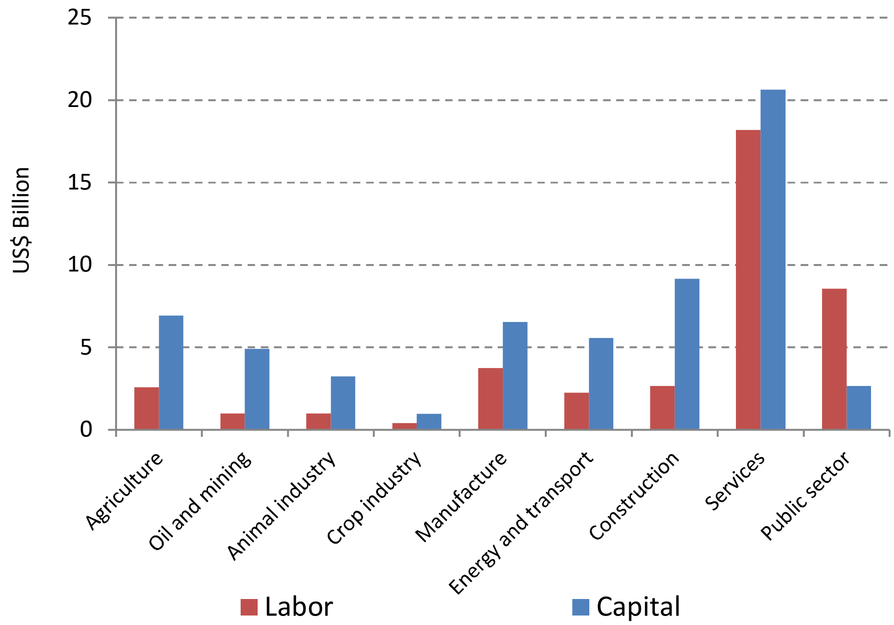


Figure 31 Remuneration of production factors
Source: Prepared with data from BCE (2021)

The construction sector has been the most disadvantaged in capital and labor remunerations. In the first case, it maintained an average growth of 12% during the period of 2009-2014. In the second one, it maintained an average growth of 18%. However, capital remuneration decreased by 9% in 2019, while labor remuneration had not grown in 2018 and 2019. (Appendix Figure A. 1a.).

Similar to the final consumption case, manufacture, agriculture, and its industrial processes are the sectors with low variation and a sustained growth in final consumption. However, these sectors present low remunerations to production factors, showing a production structure with low added value. As a consequence, the model will evaluate these sectors by aggregating them. (Appendix Figure A. 1b.). Considering these conditions, the CGE_EC define production behavior of goods and services uses a CES function by implying a minimization of production cost links two production factors: capital (K_i) and labor (L_i) (equations 6 and 7).

Demand by labor factor:

$$L_i = \left(\frac{\gamma_{L_i}}{P_{L_i}}\right)^{\sigma_i} \left[\gamma_{K_i}{}^{\sigma_i} \cdot P_{K_i}{}^{1-\sigma_i} + \gamma_{L_i}{}^{\sigma_i} \cdot P_{L_i}{}^{1-\sigma_i}\right]^{\frac{\sigma_i}{1-\sigma_i}} \frac{X_i}{t_i} \qquad \text{Eq. 6}$$

And

Demand by capital factor:

$$K_i = \left(\frac{\gamma_{K_i}}{P_{K_i}}\right)^{\sigma_i} \left[\gamma_{K_i}{}^{\sigma_i} \cdot P_{K_i}{}^{1-\sigma_i} + \gamma_{L_i}{}^{\sigma_i} \cdot P_{L_i}{}^{1-\sigma_i}\right]^{\frac{\sigma_i}{1-\sigma_i}} \frac{X_i}{t_i} \qquad \text{Eq. 7}$$

Where γ_i is the distribution parameter for each production factor, σ is the elasticity of substitution between the production factors capital and labor for each sector. P_K and P_L are the price of capital and labor, respectively. Technological and production conditions for each sector are represented by t_i.

External Markets and other elements

In general, the trade balance is usually negative as seen in *Figure 32*. Its lowest value was US$3,219 million in 2010 due to the increase in fuel imports, the exception was 2016, when the trade balance was positive with US$522 million due to reduction in manufactured products importation. During the period of 2009-2014 there was a growth of the foreign market (both in imports and exports) and, after 2015, there was a reduction in exports and imports between 26% and 18%.

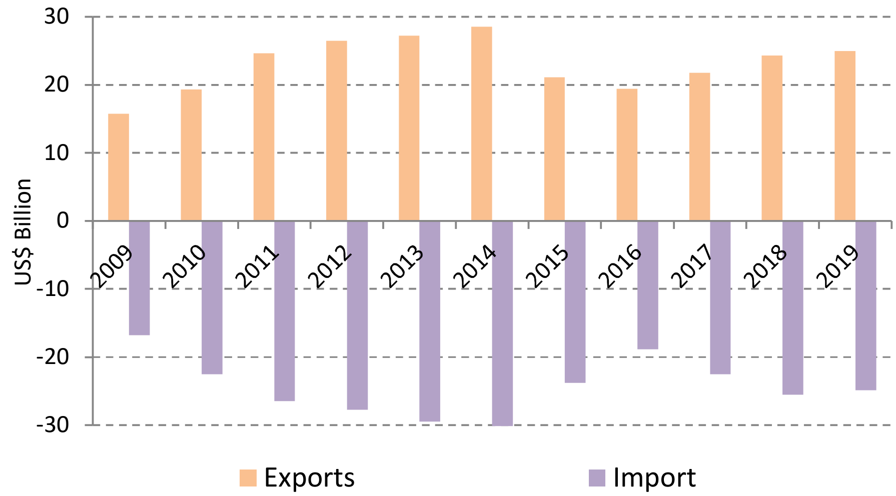


Figure 32 Historical trade balance
Source: Prepared with data from BCE (2021)

Figure 33a shows the role of the oil sector, as exports of this product allow for maintaining a balanced trade in the case of high decrease. In 2015, the oil exports decreased 26% and created a negative trade balance of US$2.7 billion in 2013 and 2014 were the highest growth of oil exports. The agricultural exports are comprised by bananas, cocoa, flowers and do not present significant variations.

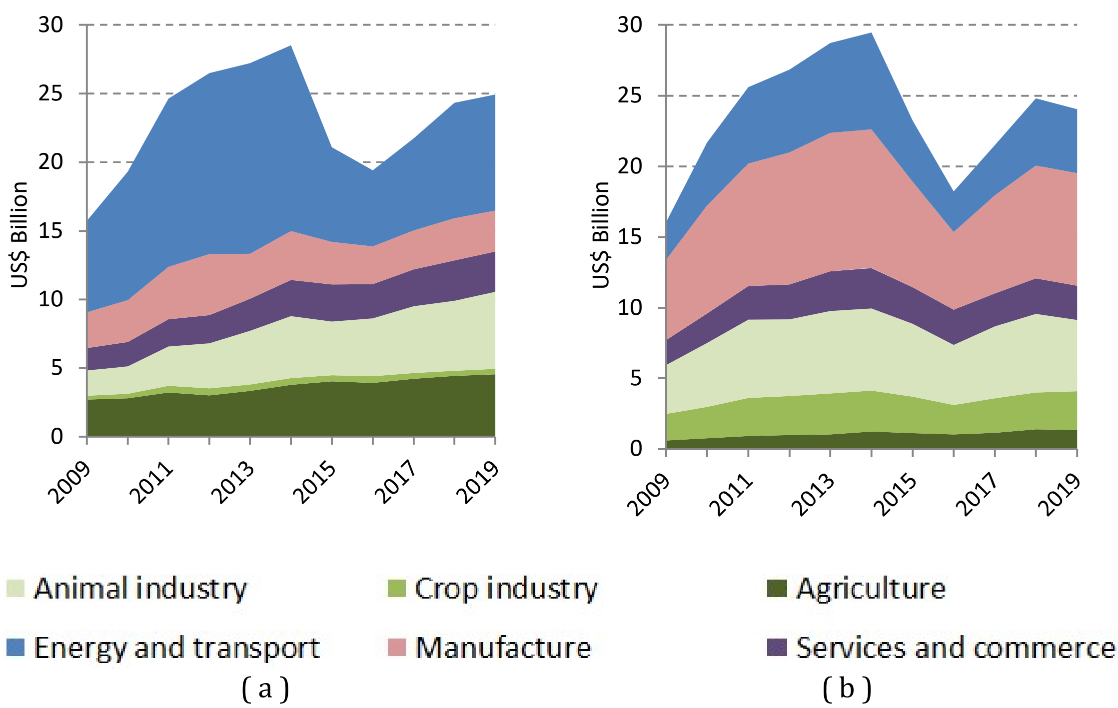
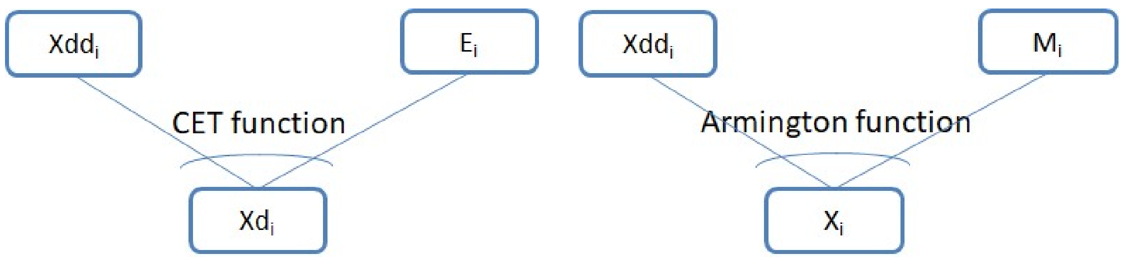


Figure 33 External market by sectors: (a) exports and (b) imports
Source: Prepared with data from BCE (2021)

Manufactured products are mostly imported and mainly they comprise of capital goods, machinery and inputs for domestic industry. These imports had dropped in 2018 (Figure 33b). Energy and transportation imports refer to fuels and raw materials for transportation, this category is the second most important in imports. In 2014, it represented 22% of all imports, with a value equivalent of US$6.4 billion, the equivalent of 6% of the same year's GDP.



(a) (b)

Figure 34 External economies model - function (a) CET (b) Armington

In this context, the CGE_EC uses two functions to determine the interaction between the domestic and external economies (Figure 34). First, a CET function is used to define local production targets (X_{di}). This means that the local production goes either for internal consumption (X_{ddi}) or exportation (E_i), linking their respective costs (p). The second function taken into account is the Armington function, which is used to define the number of goods and services that are imported (M_i) by Ecuador.

Constant Elasticity of Transformation:

$$X_{dd_i} = \frac{X_{d_i}}{aT_i} \cdot \gamma_{X_{ddi}}^{\sigma_{Ti}} \cdot p_{X_{ddi}}^{-\sigma_{Ti}} \cdot \left[\gamma_{E_i}^{\sigma_{Ti}} \cdot p_{E_i}^{1-\sigma_{Ti}} + \gamma_{X_{ddi}}^{\sigma_{Ti}} \cdot p_{X_{ddi}}^{1-\sigma_{Ti}}\right]^{\sigma_{T_i}/1-\sigma_{T_i}} \qquad \text{Eq. } 8$$

$$E_i = \frac{X_{d_i}}{aT_i} \cdot \gamma_{E_i}^{\sigma_{Ti}} \cdot p_{E_i}^{-\sigma_{Ti}} \cdot \left[\gamma_{E_i}^{\sigma_{Ti}} \cdot p_{E_i}^{1-\sigma_{Ti}} + \gamma_{X_{ddi}}^{\sigma_{Ti}} \cdot p_{X_{ddi}}^{1-\sigma_{Ti}}\right]^{\sigma_{T_i}/1-\sigma_{T_i}} \qquad \text{Eq. } 9$$

And

Armington function:

$$X_{dd_i} = \frac{X_i}{aA_i} \cdot \gamma_{X_{ddi}}^{\sigma_{ai}} \cdot p_{X_{ddi}}^{-\sigma_{ai}} \cdot \left[\gamma_{M_i}^{\sigma_{ai}} \cdot p_{M_i}^{1-\sigma_{ai}} + \gamma_{X_{ddi}}^{\sigma_{ai}} \cdot p_{X_{ddi}}^{1-\sigma_{ai}}\right]^{\sigma_{a_i}/1-\sigma_{a_i}} \quad \text{Eq. } 10$$

$$M_i = \frac{X_i}{aA_i} \cdot \gamma_{M_i}^{\sigma_{ai}} \cdot p_{M_i}^{-\sigma_{ai}} \cdot \left[\gamma_{M_i}^{\sigma_{ai}} \cdot p_{M_i}^{1-\sigma_{ai}} + \gamma_{X_{ddi}}^{\sigma_{ai}} \cdot p_{X_{ddi}}^{1-\sigma_{ai}}\right]^{\sigma_{a_i}/1-\sigma_{a_i}} \quad \text{Eq. } 11$$

The CET function is represented by equations 8 and 9. In it, γ_{Ti} is the parameter of production supply distribution, σ_{Ti} is the parameter of substitution between domestic production-exports, and aT_i is a measure of technological capacity. The Armington function is represented by equations 10 and 11. In it, the parameters have the same meanings as those of the CET function. However, they are applied to the criteria of import or local production, differing from its parameter of substitution (σ_{ai}) between domestic production-imports, along with importation costs.

Investment conditions:

$$I_i = \frac{S}{p_i} \cdot \alpha_{I_i} \quad \text{Eq. } 12$$

A crucial premise is the use of savings (S) for investment, as the demand of products for *GFCF*. The investments (I_i) are a relationship between savings (S) and goods and services prices (p_i) represented in equation 12, where α_{Ii} is the distribution parameter for investments. The equilibrium between demand and supply is the main model postulate, thus the set of equations must be in zero profit conditions.

Income Balance:

$$S_{ext} + \sum_{i=1}^{n} p_{E_i} \cdot E_i = \sum_{i=1}^{n} p_{M_i} \cdot M_i \quad \text{Eq. } 13$$

Market clearance of goods:

$$X_i = I_i + C_i + G_i + \sum_{j=1}^{n} P_j \cdot q_{ij} \quad \text{Eq. } 14$$

Market zero profit: $$p_{Xd_i} \cdot X_{d_i} = p_{E_i} \cdot E_i + p_{Xdd_i} \cdot X_{dd_i} \quad \text{Eq. } 15$$

Sector zero profit: $$p_i \cdot X_i = p_{M_i} \cdot M_i + p_{Xdd_i} \cdot X_{dd_i} \quad \text{Eq. } 16$$

The zero-profit equations are represented in equation 16. In it, the G_i represents government demand, and P, the prices of goods and services relate to export, import, domestic consumption, and internal production.

Closure selection

The CGE_EC model consists of 1,112 variables. They comprise of 12 exogenous variables and 1,100 endogenous ones, which are linked to 1,100 equations and adapted NDC conditions and requirements. The main NDC initiative goal is to reduce traditional energy sources' consumption in favor of renewable sources (Table 2). The NDC implementation implies several investments for the Ecuadorian government, with an intensive use of its production factors: capital (K_i) and labor (L_i). Capital supply is considered as an exogenous variable. The labor remuneration is the *numéraire* in the CGE_EC, so price variation of goods and services will be referenced around it. The model assumes the macroeconomic conditions in 2010 to maintain consistency with NDC goals.

Table 7 Closure selection

Sector	Variable	Description
S2	M	Import of crude oil
S2	E	Crude oil export
S2	X	Crude oil production
S2	X	Crude oil supply
S8	M	Import of oil products
S8	E	Oil products export
S8	X	Oil products production
S8	X	Oil products supply
S18	M	Import of electricity
S18	E	Electricity export
S18	X	Electricity production
S18	X	Electricity supply

The main criteria to define the exogenous conditions are the NDC action lines in the energy sector. This implies that the export (E), import (I), supply (X_{dd}), and domestic production (X_d) of the energy sectors are defined by the modeler, in consequence the energy trade balance is exogenously determined. These sectors will be defined as exogenous variables for modeling, specifically the Armington and CET functions linked to sectors 2, 8, 18 (Table A. 7). The CET and Armington functions relate to the remaining sectors, which are endogenous sectors in the model. The variations and actors' behavior due to the NDC's energy policies would be the responses of this model. In addition, the CGE_EC model considers a set of technological and parameters as exogenous. In order to correctly execute the model, trend values are assumed and its list can be reviewed in Annex Table A. 8.

The physical proportion in relation to production of each sector remains unchanged, hence the technical coefficients are considered exogenous without shocks (a_{ij}), with the exception of technical coefficients related to fossil consumption in power generation and electricity consumption. The government's ability to define public policies and the ability to define the levels of tax revenue imply an exogenous income tax rate, in order to evaluate possible increases in tax revenue or sector taxation. Eventually, an economic growth would increase taxes revenues, in absolute terms, but not as a result of the increase in tax rate. To assess it, the income tax rate is considered as an exogenous variable to evaluate possible tax variations resulting from the increase in the level of wealth in the economy. In the same vein, the household consumption taxes rate is considered exogenous to evaluate economic implications due to the taxation increase sectors, or incentives for certain sectors if appropriate.

The Ecuadorian economy's global interference is limited[12], that is, the definition of policies or changes in the Ecuadorian economy does not influence changes in the global economy. In fact, the countries that can have this global interference are very limited, such as the case of China, EU or USA, so the model defines international import and export prices as exogenous variables, allowing the changes or variations in the international market to be adjusted.

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[12] The Ecuadorian economy represent 0.11% of the global GDP

The CGE_EC model considers that the structure of public spending is constant (health, defense and other public services). In other words, a Cobb-Douglas function[13] is admitted and the fractions of expenditures in health, education, and defense do not vary during the execution of the model. This would allow evaluating changes in the structures of government spending. Families' subsistence level is exogenous to assess increases in minimum household consumption of some product or service. The fraction of income families destined to savings is typically exogenous and represented the behavior of families. Finally, considering the dollarized economy condition, an exogenous exchange rate is assumed without variation.

To execute and make the model operational, all equations and its iterations were structured in the GEMPACK. This is a suite of economic modeling software developed by the Center of Policy Studies at Victoria University, Australia. To operationalize the structure, three exogenous subsectors are created in the GEMPACK software logic: crude oil, derivative oil, and electricity. The set of 12 variables becomes exogenous for the modelling (Table A. 2).

4.3. MPC3e model

The macroeconomic model is represented by CGE_EC and the technical model by LEAP_EC. In this section, we use a soft-link approach between them by proposing the MPC3e model. This is a hybrid model based on the approach energy-environment-economy and it proposes a new approach to model climate change policies, by evaluating interactions between the economy and technological changes in the energy sector.

The MPC3e's structure considers that the LEAP_EC's energy-environmental conditions are derived from the optimal economic solution of the CGE_EC model. To maintain consistency with this study's goals, the MPC3e model considers the same NDC periods. We use 2010 as the base year to project it until 2025. Since the evaluation focus is based on technological and environmental aspects, the hybridization process begins with the structure of the energy sector in the LEAP_EC model. For it, we use the

[13] It is a particular functional form of production function developed and tested against statistical evidence by Charles Cobb and Paul Douglas.

economic, demographic, and technological data as **Drivers** (Figure 35). We consider historical behaviors and government planning, which defines the initial conditions.

Figure 35 shows the energy consumption and GHG emissions are responses to the LEAP_EC variables. Its **Outputs** allow us to calculate the variations in the economic-energy structure, so the variations become the CGE_EC's **Input** variables using an ***energy link*** module. This module uses the economic-energy ratios between the variables of the LEAP_EC and CGE_EC models. The ratios obtained must be consistent with internal and external sales prices, production costs, and import costs. It also accounts for annual variations of energy consumption by sectors quantified in monetary terms, because these are inputs that determine the shock on the CGE_EC's **exogenous** variables (Table 7).

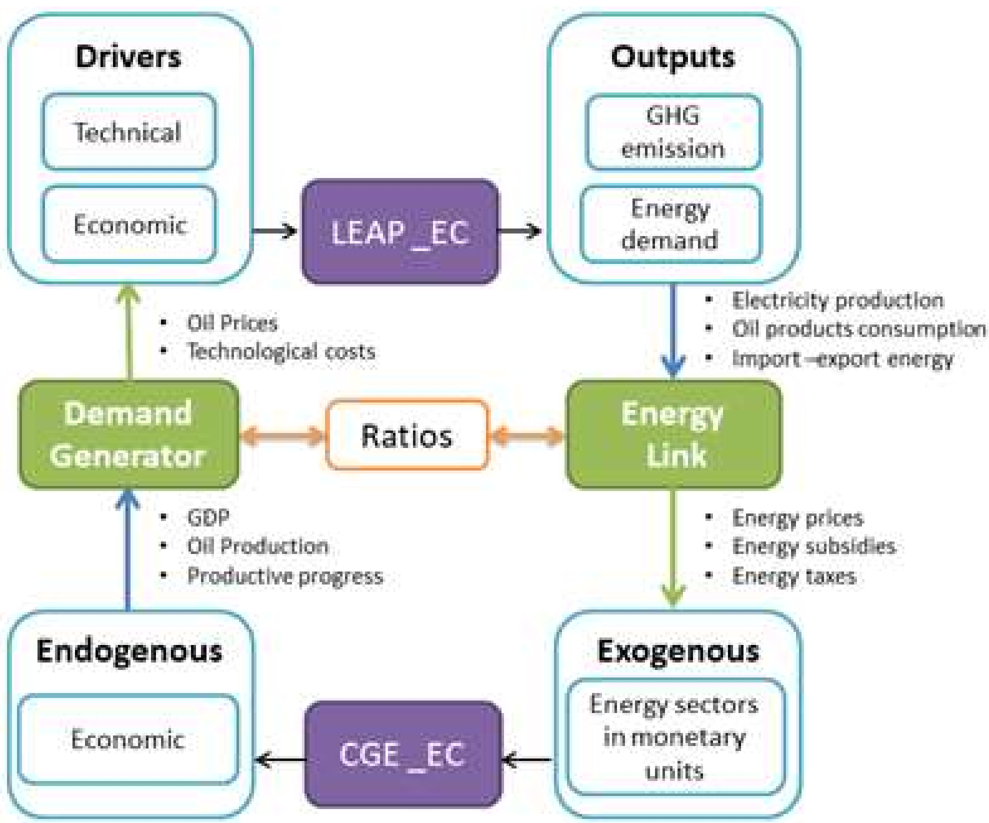


Figure 35 Schematic view of MPC3e soft-link framework

The shock on the CGE_EC's exogenous variables reflects changes in consumers' and producers' preferences since society is always reaching a new balance point. After defining these new conditions, the CGE_EC's **Exogenous** variables reflects variations in the main macroeconomic variables. These macroeconomic variations become the **Drivers** in the LEAP_EC model by using a ***Demand Generator*** module. This module uses technological changes and price variations to create new LEAP_EC's conditions (Figure 35). These new conditions will define the new levels of energy consumption and GHG emissions in the LEAP_EC model. This also generates a new shock condition for the CGE_EC's exogenous variables, creating a continuous feedback process between both models (a loop - see *Figure 36*).

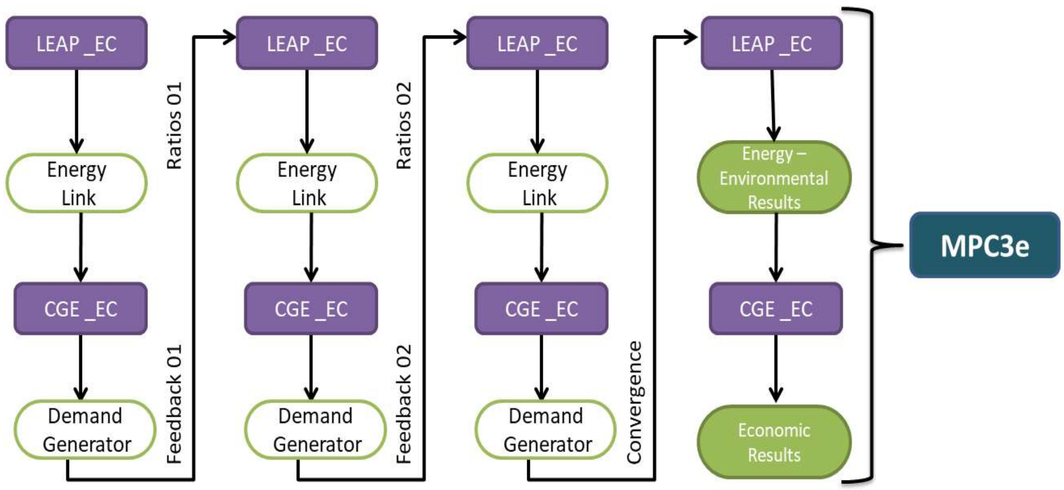


Figure 36 Schematic view of MPC3e iteration process

The GDP variation is the focus, as it is the main input variable in the LEAP_EC model and the main response variable of the CGE_EC model. The loop between models ends when we obtain the same levels of year-to-year variation in GDP between them. To obtain the same levels of GDP growth, we define **economic-energy ratios**. ***Demand Generator*** and ***Energy Link*** connectors continuously change the economic-energy ratios until determining the market conditions in which both models reach a convergence level(Figure 36). At this point of convergence, the MPC3e model is defined, in which the LEAP_EC model is initially executed to obtain energy-environmental results. This determines the shock in the exogenous variables, obtaining the CGE_EC model's macroeconomic results.

The **energy-economic ratios** could be interpreted as price or cost, depending on the variable under analysis. The ratios are defined exclusively for the exogenous variables of the model (Table 7), which are linked to the energy sectors: Crude oil, Oil products and Electricity. In the case of production variables (X_d), it would be desirable for the ratio to be as close as possible to production cost values. For variables related to external markets (M and E), the ratio should be as close as possible to import costs and export prices. For the supply variables (X_{dd}) its values should be as close as possible to domestic prices. As mentioned, the ratios vary depending on the models' convergence during iteration process, as these variations are applied as ***Energy Link*** and ***Demand Generator*** modules. By default, the initial ratios are referred to the economic-energy conditions in 2010 (base year). If the values are close to the historical data, it is regarded as a first step towards consistency between models.

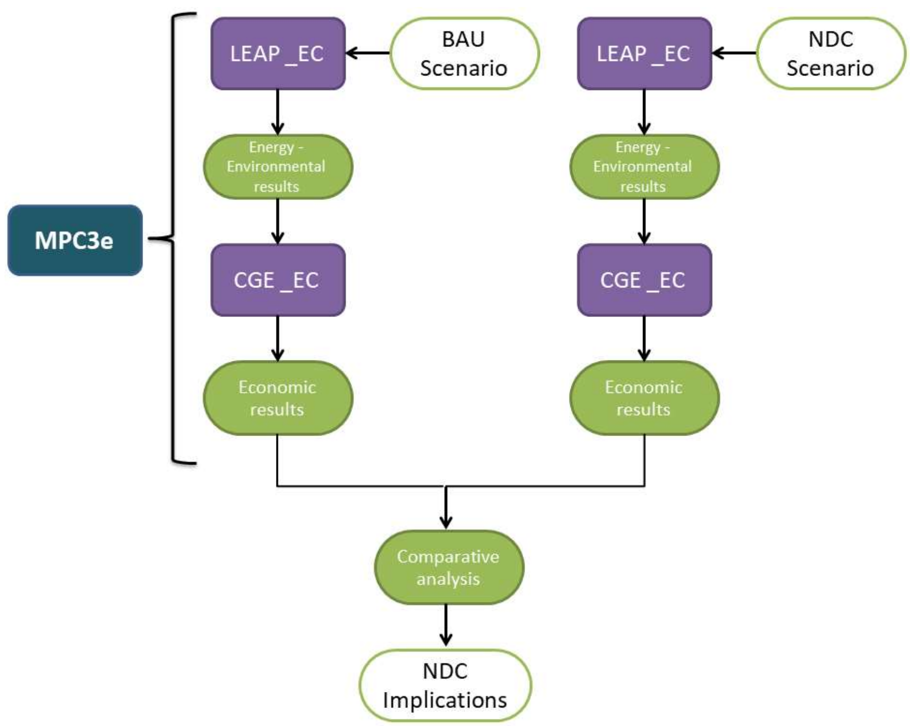


Figure 37 Schematic view of scenarios in MPC3e

Once the MPC3e model is structured, we use two scenarios to assess the NDC impacts: **BAU scenario** and **NDC scenario**. The former is the Business-as-usual Scenario, which considers the energy structure and expansion plans from 2010 (NDC base year) to 2025 (NDC horizon year). The BAU scenario defines a set of energy-environmental results related to trend conditions. The latter considers the NDC initiative to achieve the GHG reduction in the energy sector until 2025 (Table 2), because of the NDC's initiatives to accomplish the energy transition plans. The key assumptions by scenario are showed in Appendix Table A.9, it results in impacts in production, export, import, and domestic consumption of energy sources and defines a set of exogenous variables for GEM. The results of both scenarios are compared to determine the variations between them, along with its economic implications. This enables us to answer the questions raised about the NDC implementation and discuss its socio-economic impacts (*Figure 37*).

4.3.1. Modeling convergence

Figure 14 shows how both models are structured independently. The LEAP_EC structures the **initial conditions**, by considering the energy structure in 2010 and the CGE_EC structure the initial market conditions with the information of national accounts for 2010. Consequently, the two models have the same baseline and initial conditions (Table 8). Modelling starts with the **initial conditions** and defines a set of energy-environmental results (LEAP_EC), its results have impacts in production, export, import, and domestic consumption of energy sources. These results define an initial shock in the CGE_EC's exogenous variables (Table 7), which implies new market conditions. It also starts the itineration process, when the models converge, these market and energy conditions are used to structure the Business-as-usual Scenario (BAU scenario).

Table 8 LEAP_EC and CGE_EC initial conditions

Crude oil sector			
S2	**LEAP_EC (kBOE)**	**CGE_EC (Millions of US$)**	**Ratio (US$/BOE)**
Production	177,712	11,069	62.29
Export	110,910	8,951	80.71
Import	1	17,241	17.241
Supply	54,296	2,117	39.00
Oil Products sector			
S8	**LEAP_EC (kBOE)**	**CGE_EC (Millions of US$)**	**Ratio (US$/BOE)**
Production	52,855	2,938	55.56
Export	19,107	854	44.74
Import	38,480	3,283	85.33
Supply	71,317	2,083	29.21
Electricity sector			
S18	**LEAP_EC (GWh)**	**CGE_EC (Millions of US$)**	**Ratio (US$/kWh)**
Production	19,524	2,214	0.11
Export	10	13	1.33
Import	873	254	0.29
Supply	19,989	2,201	0,11

The **energy-economic ratios** are calculated to be the **initial conditions** for all exogenous variables related to energy sectors (See in Table 8). These initial ratios are consistently calculated with market values because the sectors not only consider energy products, but also the entire chain of supplies and services linked to them in the CGE_EC's economic structure. This justifies the ratios' inaccuracy with the 2010's values. The ratios change as the iteration process is carried out, changing market conditions in ***Energy Link*** and ***Demand Generation*** modules until convergence between models (Figure 36).

In 2010, the Ecuadorian GDP was US$69,555 million and had a final energy consumption of 72,280 thousand of BOE. Considering a population of 15 million inhabitants, it implies a GDP per capita of US$ 4,633/inhabitant. In the same year, there was 6,5 million of workplaces and a Gross Value Added of US$66,499 million (Table A. 3

and Table A. 4). With this information, the LEAP_EC and CGE_EC models were executed in the framework presented in Figure 35. We evaluated its results for the conditions in 2015, when there was a new social accounting matrix, allowing the itineration process.

The ***Energy Link*** module was calibrated with the new **economic-energy ratios**. It creates new conditions and results for the CGE_EC that, in turn, change the **economic-energy ratios** in the ***Demand Generator*** module. This creates new conditions and results for evaluating the LEAP_EC to acceptable levels of convergence. The GDP is defined as the convergence variable, when compared to 2015 values. The increases of capital and labor supply are considered as shocks variables to define the 2015 conditions.

Table 9 MPC3e Linking process - shock in energy sectors

	Iteration		
Variable	**First iteration**	**Second iteration**	**Third iteration**
	Crude oil		
Production	11.71%	11,71%	11,71%
Supply	-10.54%	-10,54%	-10,54%
Export	35.20%	35,20%	35,20%
Import	6.41%	1.37%	0.21%
	Oil Products		
Production	-11,78%	-11,78%	-11,78%
Supply	15,80%	23,88%	31.98%
Export	-27,98%	-35,06%	-25.93%
Import	30,90%	47,40%	63.95%
	Electricity		
Production	33,02%	33,02%	33,02%
Supply	29,67%	29,67%	29,67%
Export	360%	360%	360%
Import	-41.30%	-21.49%	5.21%
	Economic growth (Millions of US$)		
GDP_{MPC3e}	85,339	84,228	83,876
Error	-1.25%	-1.30%	-0.21%

All the soft-link process involves three iteration process. The first iteration process has acceptable results, with an error margin of -1.25%, as well as high assertiveness in the energy sector variables: oil, derivatives, and electricity. Table 7 shows the energy variables related to the external sector have the most significant errors. The ***Energy Link*** module is used to determine the most appropriate market prices, and subsequently we execute the second iteration with these new market conditions. The second iteration has an error of -1.30%. Considering new external market conditions, the economic growth is consistent with the observed rate between 2010 and 2015**,** as the variations are concentrated in the Oil products sector and external market for crude oil and electricity.

The last iteration process shocks in product imports. It obtains a GDP of US$83,876 million, implying an error of -0.21% between models when compared to the economic growth in 2015. This is an acceptable error within the process, and it finalizes the iterative process, validating the models' hybridization. Once the MPC3e is model has been defined, we proceeded to evaluate the NDC initiatives in the energy sector (NDC scenario) and compared its results with the trend conditions of the BAU scenario.

4.3.2. Modeling execution

As seen previously, the MPC3e model is used to evaluate the socioeconomic implications of the NDC, so its execution must be defined by the period of time established by the Ministry for fulfillment of the objectives and their subsequent evaluation. The model thus runs from 2010 to 2025 for both scenarios. In 2010, the scenarios start from the initial conditions according to the economic-energy ratios defined in the convergence between models (Table 8). In the base year both scenarios present the same results, although starting with different initial conditions between them.

The annual variations of the energy consumption and infrastructure expansion are referenced to the year 2010 and interpreted as a shock in the exogenous variables of the model (Table 7). The hydropower increase in the NDC scenario implies a variation of the technical coefficient of power generation according to the power expansion planning to achieve the electricity supply objectives in 2025 (MERNNR, 2018b), while in the BAU scenario there are no variations in the technical coefficients, that is, the trend of power generation remains constant.

Table 10 MPC3e execution model - shock in exogenous variables

Year	2015		2020		2025	
Crude Oil						
S2	**BAU**	**NDC**	**BAU**	**NDC**	**BAU**	**NDC**
Production	11.71%	11.71%	-2.44%	-2.44%	-12.71%	-12.71%
Supply	-10.54%	-10.54%	11.55%	11.55%	11.55%	11.55%
Export	25.05%	25.05%	-5.93%	-5.93%	-21.15%	-21.15%
Import	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Oil Products						
S8	**BAU**	**NDC**	**BAU**	**NDC**	**BAU**	**NDC**
Production	-11.78%	-11.78%	10.64%	10.64%	10.64%	10.64%
Supply	23.89%	32.43%	39.97%	-66.72%	59.52%	27.34%
Export	-25.06%	-27.98%	-1.89%	17.42%	-11.78%	16.26%
Import	47.40%	30.90%	58.48%	22.85%	89.56%	44.52%
Electricity						
S18	**BAU**	**NDC**	**BAU**	**NDC**	**BAU**	**NDC**
Production	33.02%	33.02%	59.40%	124%	85.80%	124%
Supply	29.67%	27.15%	49.86%	62.82%	73.27%	81.68%
Export	-91.36%	72.76%	7.18%	2,048%	242%	1161%
Import	0.00%	-41.30%	0.00%	-100%	0.00%	0.00%
Consumption	36.66%	38.11%	65.85%	70.99%	86.43%	95.96%
Production factors						
Label supply	12.01%	12.01%	20.49%	20.49%	28.02%	28.02%
Technical Coefficients						
ai	**BAU**	**NDC**	**BAU**	**NDC**	**BAU**	**NDC**
Fossil Power	86%	1.00%	86%	-37%	86%	-37%
Hydropower	86%	520%	86%	216%	86%	216%

On the demand side, the initiatives imply increases in electricity consumption from renewable sources, so the NDC scenario considers gradual increases in electricity consumption (Appendix Figure B.1) until meeting the objectives in 2025, while the BAU scenario considers the electricity consumption according to the trend conditions.

In both scenarios, the oil sector is defined by the national oil production planning of the national oil company, this planning is periodically adjusted by the government regarding production limits, while the crude oil supply is defined by the consumption chain in the MPC3e, where the supply from refineries is prioritized to satisfy the domestic consumption of derivatives and the surpluses are exported. Considering that Ecuador is a net crude oil exporter, oil imports are not considered in the model (Annex Figure D. 2 and Figure D. 3).

The MPC3e assumes the total availability of the installed capacity for oil refining, considering its levels of efficiency and quality of products. These characteristics imply production of low-quality derivatives that does not satisfy domestic demand, so that some products are imported and the surplus of low-quality products not consumed domestically is exported. In the same way, electricity production and the technical coefficients for power generation are defined by government expansion plans, where the model prioritizes internal consumption, with surpluses allocated for export.

The LEAP_EC model provides the energy and environmental responses in absolute terms, which are quantified in relative terms (Table 10) to define the shocks from exogenous variables in the MEG_EC and obtain the macroeconomic responses of these variations. Although it is true that the MPC3e model is static, since the results are obtained for a specific year, this calculation process can be carried out over other periods to present dynamic results that allow the identification of trends and behaviors between scenarios. Hence, the calculations and results in this study are carried out with a five-year range.

4.4. Conclusion

Model hybridization is a process that has been validated and gained relevance in the last years. Several authors are exploring this alternative approach, as it provides significant contributions in environmental policy assessments, whether global or regional. This study achieves the hybridization of a technical model and a macroeconomic model, LEAP_EC and CGE_EC (respectively). It differs from previous studies in their regional application and by using characteristics of a developing economy. The literature review showed that there are applications to the Ecuadorian reality of the LEAP model and general equilibrium models, but they were independent.

The LEAP_EC model presents a high level of robustness, reflecting the energy and environmental characteristics. As a demand-driven model, we proposed the final energy consumption as its main response variable. The main input within the key assumption is economic growth, which was represented by the variation in GDP, an approach that allows a linking with the CGE_EC.

The variables related to energy sectors are defined as exogenous in the CGE_EC, to define the Energy link and Demand Generator modules. The variations in the energy's supply and demand are shock references in the CGE_EC model to obtain the new market conditions. This implies an iterative process between the models until the appropriate levels of convergence are obtained. We highlight the high consistency of the results between the models, as well as the correct use of the link modules, which are based on an energy-economy ratio. At the end of the fourth iteration, we obtained the convergence. It demonstrates the hybridization of the LEAP_EC and CGE_EC models, defining the MPC3e model.

5. Results and Discussions

We divide this discussion into two sections. The first one is an evaluation of the technical aspects related to investment and savings due to GHG reduction for each NDC initiative (NDC traditional analysis). The second section analyzes all the NDC initiatives interacting together in two scenarios: BUA and NDC. The first one represents the Business-and-usual conditions and the second one considers the NDC initiatives. For it, we use the MPC3e results, which obtained the energy-environmental-economic implications of its implementation (MPC3e analysis). This allows us to answer the questions raised in this thesis.

5.1. NDC traditional analysis

NDC's expectations concentrate in two initiatives: hydropower expansion (the supply side) and the PEC program (the demand side). Both imply a reduction of 6,942 $GgCO_{2\text{-eq}}$. This is the equivalent of 76% of the NDC proposal in the unconditional scenario and reflects the marginal contribution from other initiatives. The OGE&EE program provides a productive use to a sub-product, currently considered a waste, implying positive results. However, its energy savings are debatable, they are higher than expected with hydropower expansion (Table 11). This project would have an investment return of 1.18 years, a fairly optimistic figure in this kind of project. The OGE&EE program *has oversized* its estimations.

The transport initiative has the lowest GHG reduction and the second-highest requirement of state investment. This entails an investment ratio of US$26.58 by $kgCO_2$ avoided, a value that exceeds the limits of comparison with other initiatives. The main goal of this initiative is not necessarily the reduction of GHG, as the environmental aspects are collateral products of this project.

The mechanisms and initiatives defined by the NDC are consistent with its goals. It is remarkable that 89.91% of the GHG reduction is concentrated in the energy sector and the remnant 10.19% of GHG reduction concentrates in the other three, resulting in a potential reduction not yet explored in these categories. There would also be a preferential bias towards the energy category due to opportunities' seizing. Its results are categorized into energy production and efficient consumption initiatives. The hydropower initiative would be the largest investment one, accounting for 56.06% of it, and contributing to 56.17% of GHG emissions' reduction[14]. The PEC program has a contribution of 28.54% in GHG reduction without significant investments. This is because the costs in technological change fall on the consumers, with a limited participation of the state when compared to previous projects. The hydropower expansion implies an increase of 76.91% in electricity production, a value that would be 1.55 fold than the electricity consumption matrix. This would result in significant electrical surpluses for regional exports, production diversification, or domestic consumption. With the support of the PEC program, the population would consume 50% of this surplus.

[14] Methane emissions are not accounting due to its low emissions levels in "run-of-river" power plants

Table 11 Performance of energy supply initiatives

Initiatives		GHG Reduction	Energy Production	Energy Savings	
		Index (US$/kg$CO_{2\text{-}eq}$)	Index (US$/kWh)	Index (US$/BOE)	Payback[15] (years)
1	Hydro	0.98	0.29	423	4.75
2	OGE&EE	1.23	0.91	105	1.18
3	NCRE	2.37	1.32	699	7.85

High levels of investment in hydropower expansion have the best GHG reduction performance by the level of investment. The reduction of each kg$CO_{2\text{-}eq}$ entails an investment of US$0.98 by kg$CO_{2\text{-}eq}$ reduced. The NCRE initiative would require US$2.37 by kg$CO_{2\text{-}eq}$ reduced investment for the same GHG reduction level. The transport initiative implies an investment of US$ 26.58/kg$CO_{2\text{-}eq}$ reduced. This characteristic is justified in the program's aim, which is to improve urban mobility and optimize its transport infrastructures. The environmental benefits are collateral issues. Its implementation involves a 720% increase in electricity consumption in the transportation sector. The debate focusses on electricity generation sources to supply this significant increase is crucial, as power generation based on traditional fuels implies counterproductive results.

The PEC program has a similar issue, as its implementation involves increasing 5,463 GWh in residential electricity consumption. It is linked to the reduction of 3.8 million BOE, the equivalent of a 70.94% reduction in consumption of LPG in this sector. The use of fossil-fuel-based electricity generation technologies in Ecuador was examined by Ramirez et al. (2019). They argue that the fossil-fuel-based electricity provide a general picture of the current debate concerning the transition pathway.

On the energy savings indicator, the OGE&EE program would be the most convenient with an investment of US$ 105 for each BOE saved. The development of NCRE has an index of US$ 699/BOE, and the payback of the OGE&EE project was estimated in 1,18 years. This is the fastest recovery of all initiatives, a characteristic of the productive use of waste, such as gas flaring. It involves environmental and economic

[15] Estimated value considering oil product import prices

benefits and in 2016 the OGE&EE net savings were US$607 million (MEER, 2017a). Gas flaring can be used to produce LPG, natural gasoline, and electrical energy generation.

5.2. NDC analysis using MPC3e

In the BUA scenario, GHG emissions are estimated at 53,150 $GgCO_{2\text{-eq}}$ for 2025, corresponding to a 1.57-fold increase from base year emissions (Figure 38a). NDC initiatives' implementation implies a reduction of 7,396 $GgCO_{2\text{-eq}}$ (13.93%) by 2025 (NDC scenario). This result is close to the NDC goals, which propose a GHG reduction of 13.47% in 2025 (Figure 1). There is consistency between the results obtained by the MPC3e model and the NDC goals, included in the assertiveness of the NDC initiatives for the energy sector.

The MPC3e model foresees that energy initiatives would represent 81.01% of the total GHG reductions achieved by 2025, while the traditional analysis estimated at 89.91%. The energy initiatives' implementation is necessary to determine the goals proposed in the NDC, as it reflects the contribution of the other categories in GHG reduction.

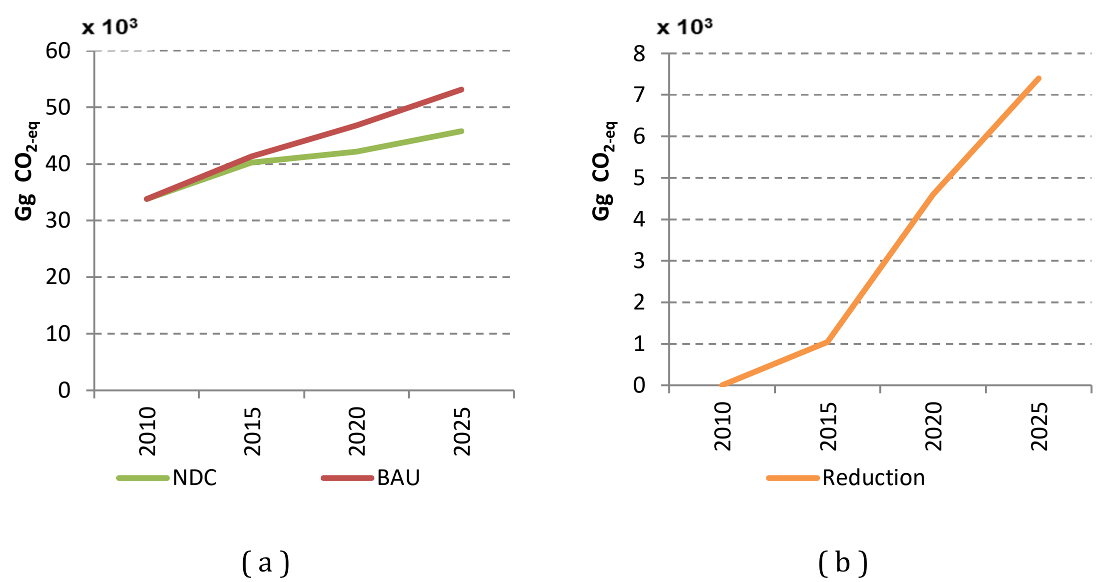


Figure 38 GHG results due to NDC implementation: (a) scenarios and (b) reduction

Figure 38b shows that no significant reductions would be obtained during the first five years of implementation (2010-2015). The average annual reduction would be 939 $GgCO_{2\text{-eq}}$. There is a significant increase in the GHG reduction from 2017 onward, reaching an average annual reduction of 5,997 $GgCO_{2\text{-eq}}$ during the last implementation period (2020-2025). There are two different periods: one of transition and one stationary. The first one is related to the required investments and technological transitions, a period with intensive use of capital. In the second period, there is an expectation of investment return, as a result of energy savings or external income derived from energy sales.

Figure 3 shows the emissions related to energy sector are: carbon dioxide, methane, and nitrogen dioxide. CO_2 emissions are preponderant between them; this condition does not change for the two scenarios. For 2025, the CO_2 emissions represent 98.51% and 98.33% of the total GHG in the BAU and NDC scenarios, respectively (Figure C. 1). The reduction achieved by the NDC initiatives is 7,396 $GgCO_{2\text{-eq}}$, 99.65% of which comes from CO_2 reduction, while the remainder is related to methane and nitrous dioxide reductions.

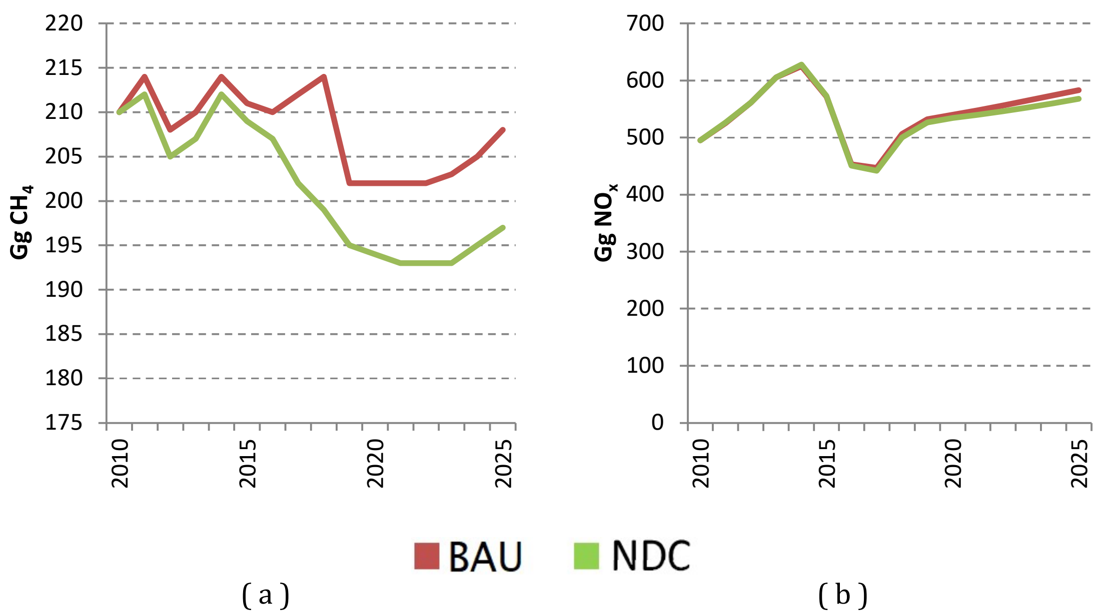
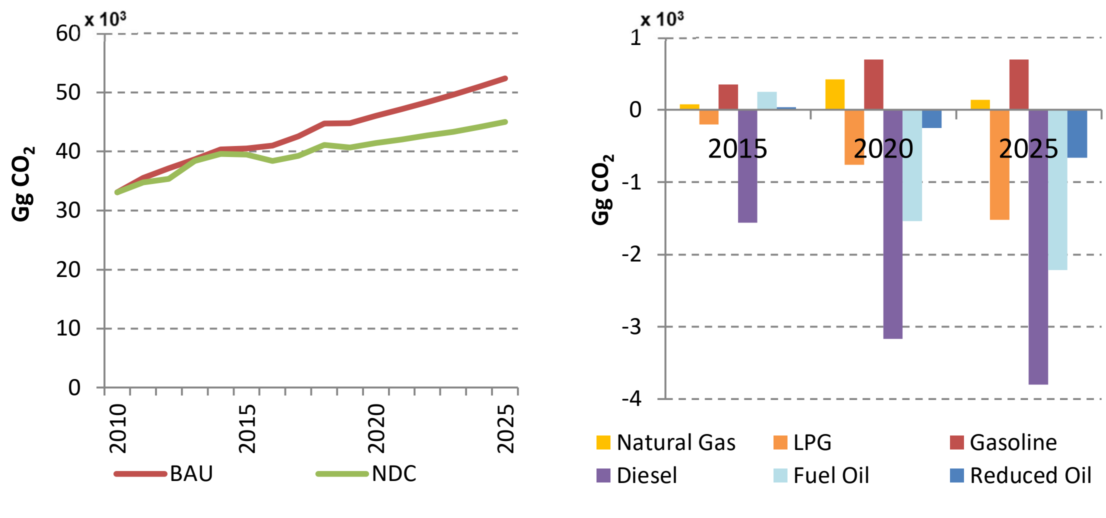


Figure 39 Gases reductions in scenarios: (a) methane and (b) nitrous oxide

In 2025, the methane emissions in the NDC scenario would be of 197 $GgCH_4$, a reduction of 5.29% when compared to the BAU scenario. Figure 39a shows that this reduction is accentuated during the period 2017-2023. In fact, there is a peak in methane reductions in 2018, the equivalent of 7% of emissions from the BAU scene (Figure C. 3). However, there is an increase of these emissions in 2020. From 2023 on, there would be an increase in CH_4 emissions due to the use of natural gas for power generation. The Figure 39b shows that the NO_2 emissions do not present significant variations in both scenarios, but there would be a slight reduction in the NDC scenario from 2023 on. It would reach 568 $GgNO_2$ by 2025, implying a reduction of 2.57% in comparation with the BAU scenario. This is due to fuel oil savings and the increase of natural gas consumption for power generation, which implies a slight increase in methane emissions. So, the NDC initiatives would not have significant effects on NO_2 reductions.



(a) (b)

Figure 40 Carbon dioxide reductions by (a) scenarios and (b) fuels

Figure 40a shows that the NDC initiatives in CO_2 emissions have more implications than CH_4 and NO_2 emissions. The reduction of 7,370 $GgCO_2$ would be is equivalent of 14.08% of BAU scenario emissions by 2025. From 2010 to 2015 there is a transition period with variability in CO_2 reductions and from 2015 to 2025 there would be an annual in CO_2 reduction (Figure C. 3).

Figure 40b shows that the CO_2 reductions are related to the decrease in consumption of diesel and fuel oil. In 2025, the reduction of diesel used in automobile production would imply a reduction of 3,800 $GgCO_2$. The reduction of fuel oil for generation to supply the national grid would imply 2,218 $GgCO_{2\text{-eq}}$ less atmospheric emissions. It is strategic to guarantee the supply of hydropower to large consumers achieve reduced fuel consumption. Note that the LPG reduction implies GHG reductions (Figure 40b).

We conclude that it is feasible to achieve the NDC goals by maintaining the current trend conditions. The transition to less polluting energy sources is also possible, especially for power generation. In the next sections, we explore the GHG reductions implications int eh country´s energy-productive structure, as well as the macroeconomic impacts. The discussion is separated into three sections: environmental results, energy aspects and economic implications. Through this analysis we will evaluate if the productive capacity is appropriate, the energy chain and economic implications. The GHG reduction goals proposed by the NDC are feasible for the country's energy-productive structure, which answers the first question of this study.

5.2.1. Environmental Results

GHG emissions’ transformation in the BAU scenario would be 14,821 $GgCO_{2\text{-eq}}$. NDC implementation would reduce it to 6,482 $GgCO_{2\text{-eq}}$ by 2025, representing 71% of the GHG reduction planned in the NDC. The NDC will have a greater impact on energy transformation processes than energy demand (Figure 41a), which reflects a high concentration in the transformation processes. Figure 41b shows that the final demand would not present a GHG reduction trend until 2020. In fact, there would be a slight increase in emissions in 2015, probably due to the expansion of power coverage and attention to repressed demand. However, from 2020 on, there would be a reduction, achieving 11.07% in 2025 when compared to 2010.

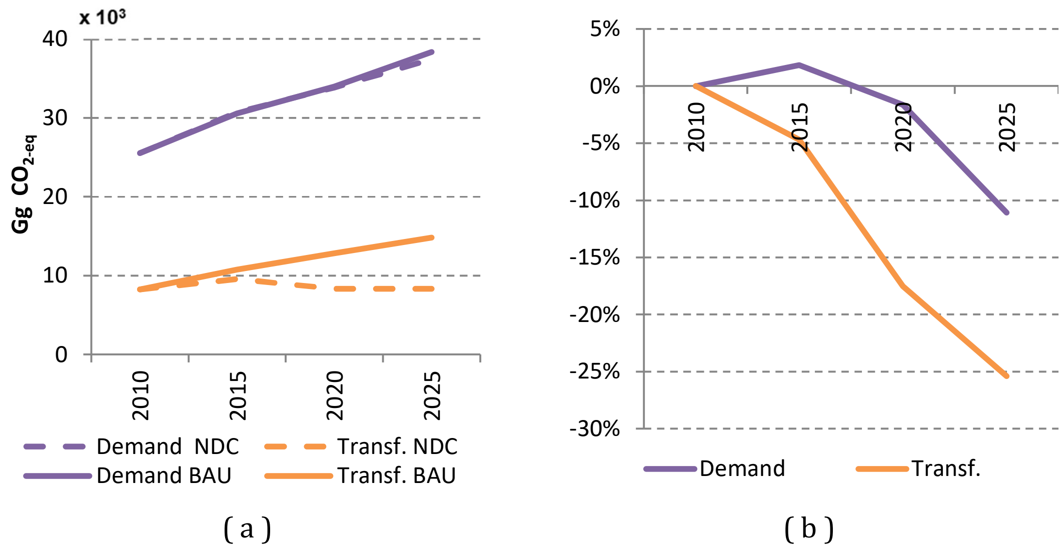


Figure 41 GHG emission (a) scenarios and (b) base year reduction

The opposite situation occurs during the transformation process. It would gradually increase the GHG reduction when compared to the base year, which implies a reduction of 17.51% by 2015. It will achieve a reduction of 25.41% in 2025, when referred to the base year (Figure 41b). Although it is true that the transformation processes present significant reductions (Figure 41a), it represents 19.27% of the GHG emissions forecast for 2025. The energy consumption would represent 49.84% of the GHG emissions for this scenario. It would be desirable for NDC to consider more initiatives in the energy consumption, with an emphasis on the transportation sector.

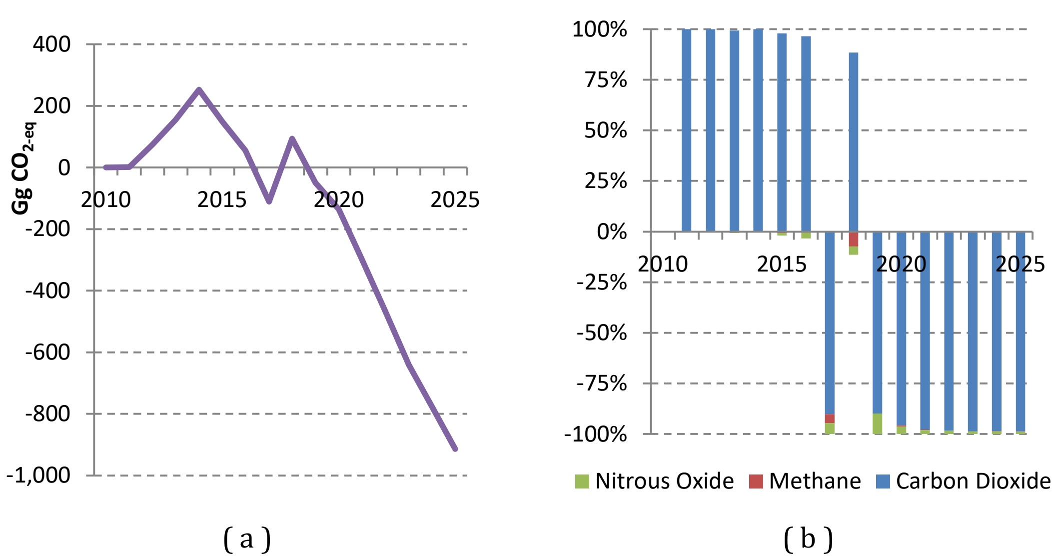


Figure 42 Final demand (a) GHG reductions and (b) sharing GHG

Despite NDC's implementation, the first five years presents a GHG increase (Figure 42a). This is due to the rapid economic growth and attention to repressed demand. However, from 2020 on, there is a gradual and sustained GHG reduction that lasts until 2025 due to the full implementation of energy efficiency programs. Figure 42b shows that the NDC initiatives mainly involve CO_2 emissions especially during 2015-2020, when there are reductions in CH_4 and NO_2 emissions due to gas flaring reduction and gas used to generate power for automakers.

Power plants are the main GHG emitters in the energy transformation, representing 92.49% of total. NDC initiatives should focus mainly on refineries and gas centers, as they represent 5.20% and 2.31%. According to the BAU scenario, emissions would increase by 1.79 when compared to the base year (Figure 43a). The NDC scenario seems to keep emissions at a stable level, reducing emissions by 43.74% when compared to the BAU scenario (Figure 43b).

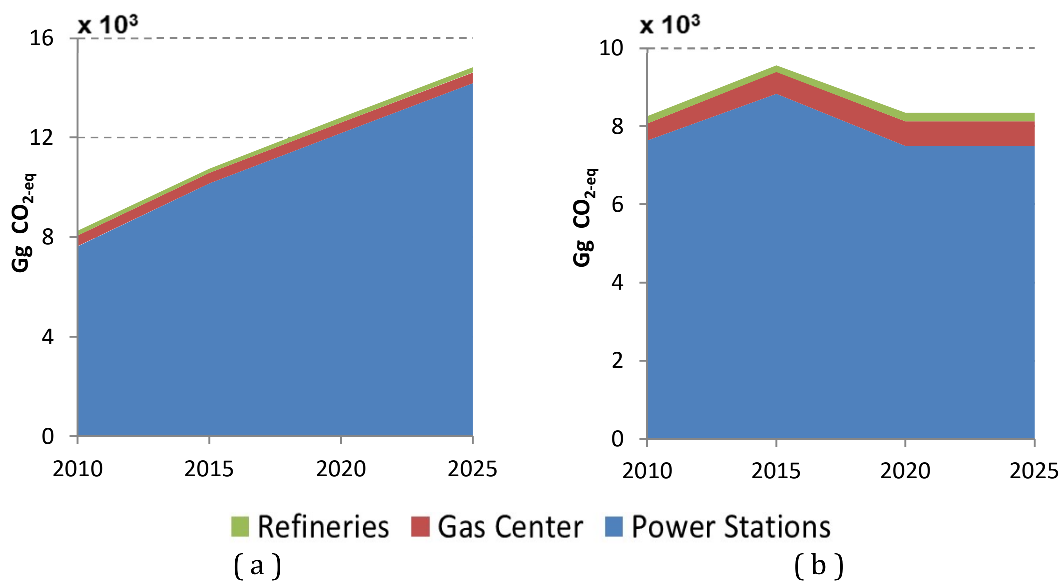
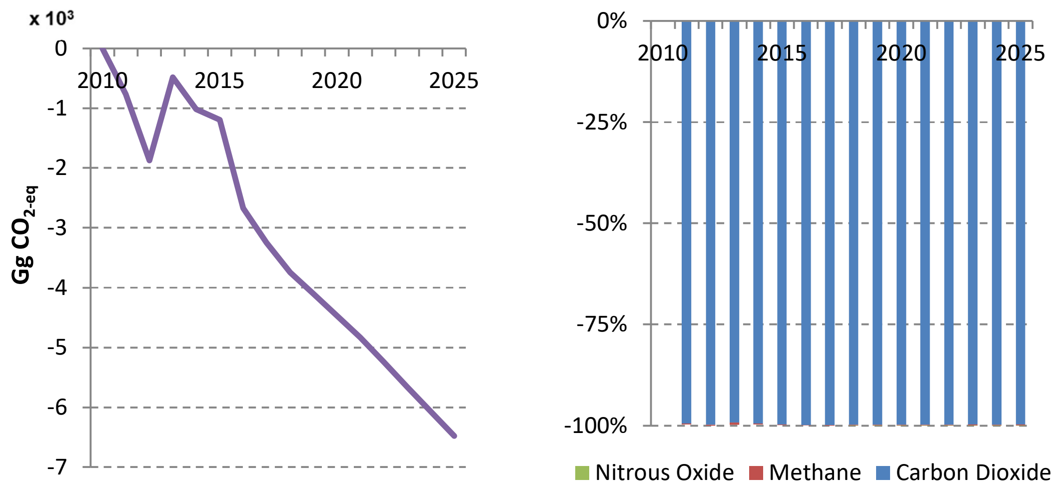


Figure 43 GHG emissions in transformation in scenarios: (a) BAU and (b) NDC

The NDC implementation would imply a GHG reduction of 47% in Power Stations by 2025, the equivalent of 6,686 GgCO2-eq in relation to the BAU scenario. The OGE&EE

project (Table 11) implies an increase of 48% in gas emissions, the equivalent of 204 $GgCO_{2-eq}$, due to the associated gas used for electricity generation. Despite this undesirable condition, there is a positive balance due to reduced fuel oil use to generate electricity. The GHG emissions' participation among the transformation centers would not provide significant variations and power plants would be considered the main GHG emitters in this category.



(a) (b)

Figure 44 Transformation (a) GHG reductions and (b) sharing GHG

NDC's initiatives have plausible results in the transformation sector when compared to the final demand with intra-annual GHG reductions, which are concentrated in CO_2 emissions. As a result of the smaller consumption of diesel and fuel oil in power generation. In the final demand, GHG reduction would be concentrated in the residential and transportation sectors, with no major impact on agricultural, industrial, or service sectors (Figure 45a). The NDC scenario implies a GHG reduction of 32.09% and 0.35% in residence and transportation sectors by 2025, respectively. However, there would be an increase of 13.29% in other sectors, a value equivalent of 696 $GgCO_{2-eq}$. The NDC scenario implies a GHG reduction of 1,611 $GgCO_{2-eq}$ in final energy demand by 2025 and 95.22% would be the result of the PEC program implementation in the residential sector.

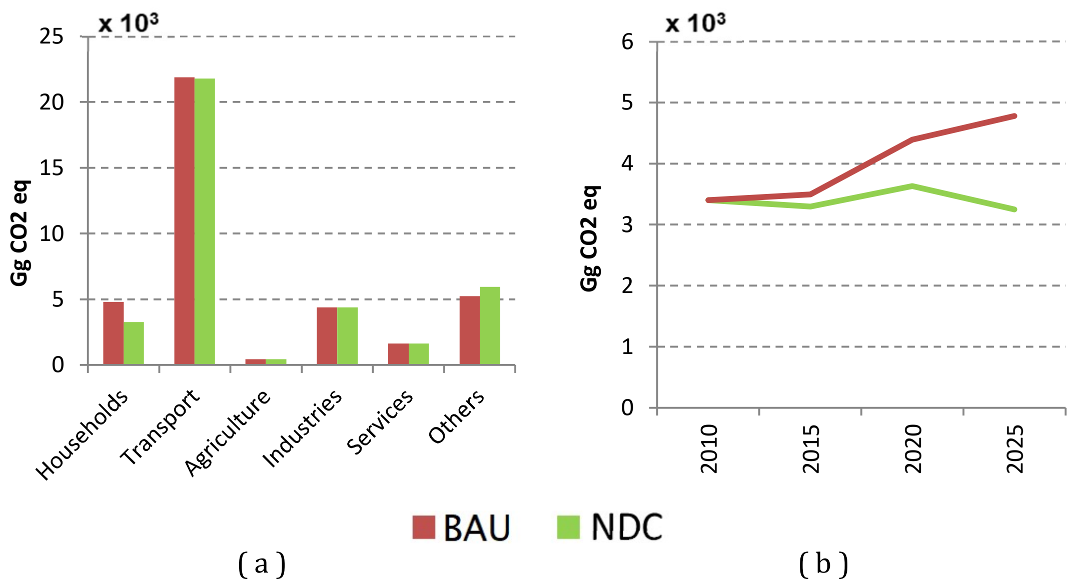


Figure 45 GHG emissions in scenarios: (a) sectors and (b) households

The BAU scenario foresees a GHG increase of 1.40-fold when compared to 2010 in the residential sector due to the LPG consumption for cooking, which means that 4,780 kBOE would be emitted in 2025. NDC initiatives guarantee a stable level in GHG emissions until 2025 (Figure 45b) and imply a GHG reduction of 4.56% when compared to the base year. The implementation of the PEC program would be a success among energy-environmental policies (Table 2), due to the use of electricity produced by hydropower plants with competitive prices.

5.2.2. Energy Aspects

The NDC initiatives' implementation implies a reduction of 2.29 million BOE in final energy demand (Figure 46a), a reduction of 2.08% with respect to the BAU scenario in 2025. Failure of its implementation would imply energy consumption of 110 million BOE in 2025, 1.52-fold energy demand in 2010. These results are concentrated in residential and transport sectors. Figure 46b shows that the results would be accentuated from 2015 on, as there would be a transition period five years from the implementation.

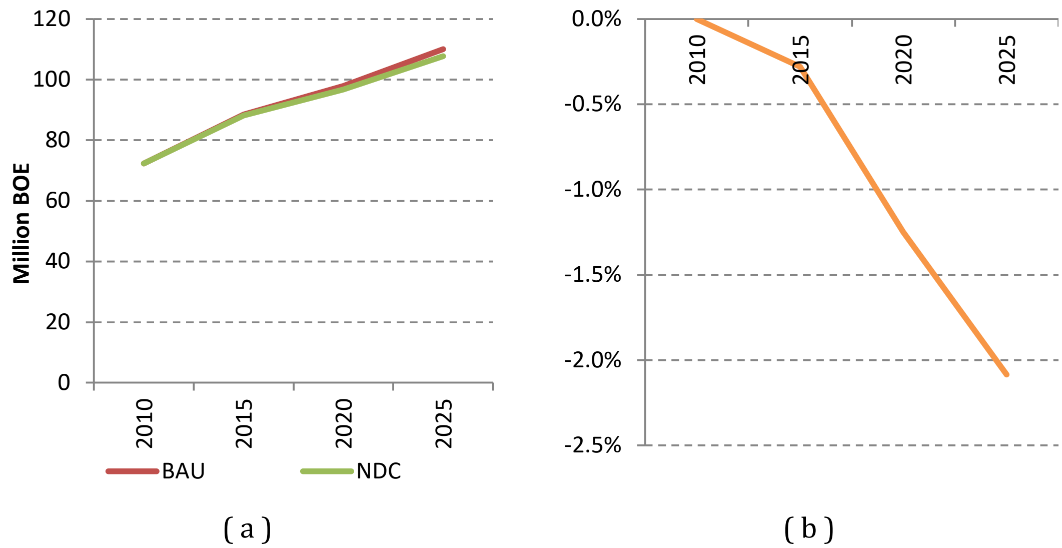


Figure 46 Energy demand: (a) scenarios and (b) reduction

Energy demand reductions are not favorable when compared to GHG reductions. Despite the NDC implementation, the consumption in 2025 would be 107 million BOE, a value 1.49-fold compared to the energy demand in 2010. GHG reductions are not only due to energy consumption, but also to the consumption of less polluting fuels, such as the reduction of LGP consumption in the residential sector, instead using electricity for cooking.

NDC implementation in household sector (summarized by the PEC program) obtaining energy savings of 2.14 million BOE for 2025. We highlight that the main beneficiaries of this program would be households located in urban areas (Figure C. 4), with the highest concentration of inhabitants, as well as the greatest electricity coverage, implying the existence of previous electrical infrastructure to facilitate penetration of the proposed technology. Banerjee *et al.* (2016) observe a similar phenomenon. They conclude that the induction stoves programs are feasible in highly electrified areas.

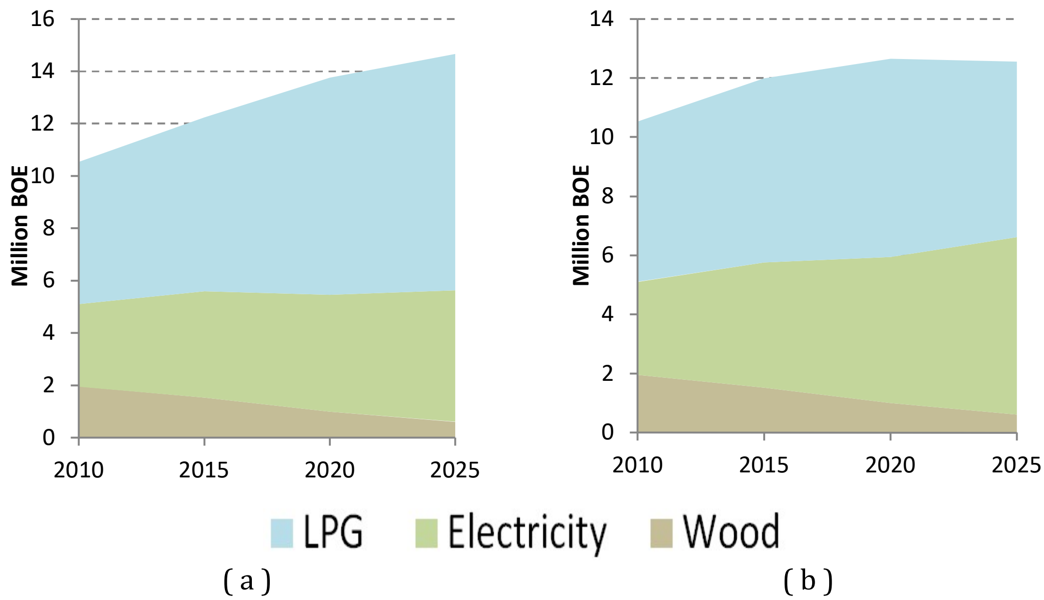


Figure 47 Households energy consumption in scenarios: (a) BAU and (b) NDC

Household consumption would be 14.66 million BOE in 2025 (Figure 47a), while it would imply a consumption of 12.55 million BOE for the same year in the NDC scenario (Figure 47b). This means a reduction of 14.41% and initiatives in the residential sector would concentrate 92.19% of energy savings in final consumption. Figure 47b shows that, during the implementation period, there would be stabilization in the electricity demand curve until 2025. The peak observed in 2015 is the result of the implementation, and the 2025 valley is the product for the substitution of LPG for electricity.

The country has insufficient LPG production to satisfy local demand, implying significant GLP imports. By 2025 in BAU scenario, LPG imports are estimated to be 10 million BOE. The NDC scenario implies a 61% reduction in imports, with imports of 3.90 million BOE by 2025. Domestic LPG production would have to satisfy the local LPG demand. The PEC program implies a reduction in 10.66 million barrels of LPG, but there would be an increase in electricity consumption by 19.53% in 2025 in the household sector, reinforcing the need for power expansion programs. In addition, in both scenarios, the use of firewood (mainly used for cooking in marginal sectors) would decrease, reaching a consumption of less than 144 thousand tons of firewood by 2025.

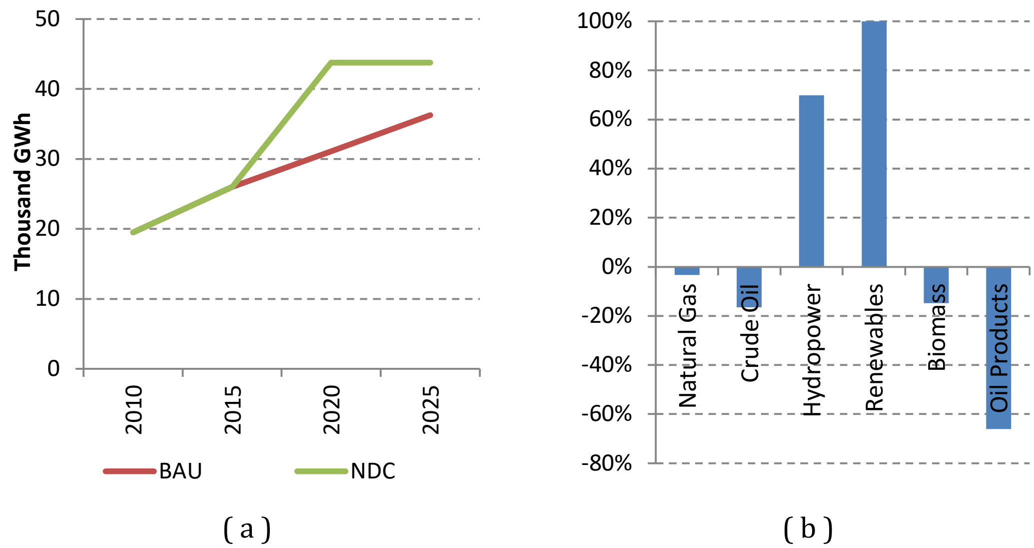


Figure 48 Forecast power production (a) and inputs in NDC scenario (b)

The expansion plan considers an increase in electricity consumption of 36,275 GWh and 43,752 GWh by 2025 in the BAU and NDC scenarios, respectively (Figure 48a). This brings up the discussion about the type of technology and fuel sources for power production. As seen previously, the NDC initiatives envision the increase using hydropower potential, so power generation efficiency would increase from 44% in the BAU scenario to 67% in NDC scenario. The NDC scenario envisions increased hydropower generation of 13,858 GWh, the equivalent of 1.21-fold hydroelectric production in the trend scenario, and thermal power generation would be reduced by 48.76%.

NDC scenario prioritizes alternatives sources. In fact, the renewable sources increase by 100%, as seen in Figure 48b, but this represents only 0.17% of all energy consumption, so the NDC initiatives need be more aggressive regarding renewable energy sources. An important NDC result is the reduction of oil product consumption by 66.06%, the equivalent of 18 million BOE, which implies a significant reduction in GHG emissions (Figure 43).

Figure 49a shows that oil products' consumption is the main input for power generation in the BAU scenario, representing 53.55%. The NDC scenario reduces its participation to 22.75%, so hydropower would be the main source of power generation, representing 51.19%. The NDC implications seen in 2015 are due to OGE&EE project, which is a rapid response project. These implications would be accentuated in 2020, due to operations of new hydropower plants.

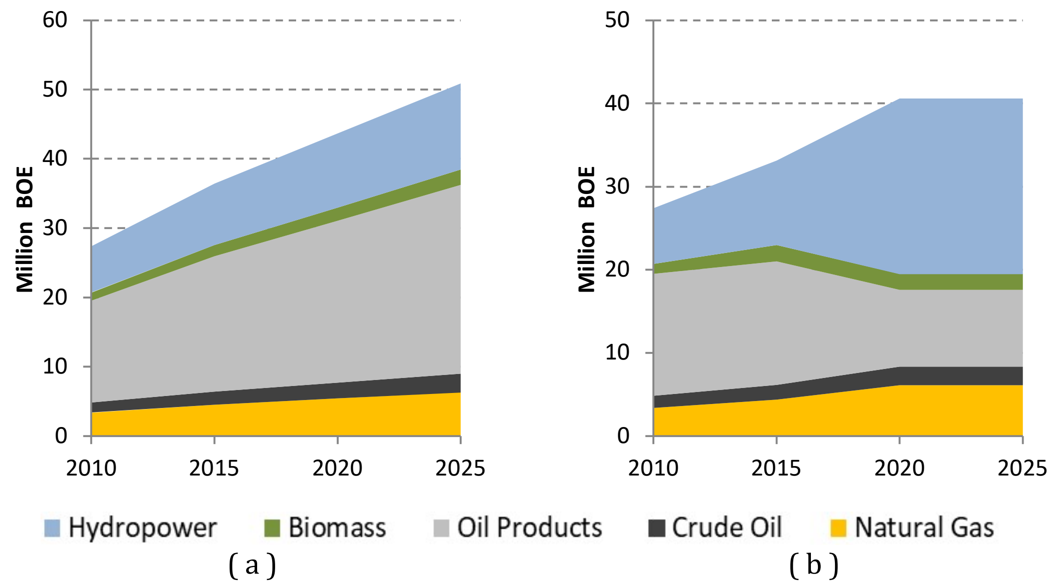


Figure 49 Inputs in Power generation in scenarios: (a) BAU and (b) NDC

The NDC scenario would imply a 14.84% reduction in biomass consumption for power generation, the equivalent of 122 thousand tons of firewood, as seen in Figure 49b. This is a collateral effect due to cogeneration and the use of a combination of sugarcane bagasse and reducing oil as fuel in self-generating plants. In the same scenario, there would be a 3.35% decrease in natural gas consumption for thermopower generation, due to flare reduction (OGE&EE program).

The NDC scenario implies a 20.12% reduction in power plants inputs, the equivalent of 10.24 million BOE, concentrated in a reduction of oil products. Because hydropower generation is a more efficient transformation process than thermopower generation, its increase in the energy mix implies more efficient power generation. This involves two significant benefits: a stabilization of the input curve for power generation and achieving electricity self-sufficiency with surpluses (Figure 50a).

However, this self-sufficiency would be limited to a period of 10 years. Thereafter, electricity importation will have to resume to supply domestic demand, mainly due to the growth of energy consumption in the industrial and transport sectors.

It is necessary to define energy efficiency policies in these sectors or alternative technologies to take advantage of the surplus of available electricity.

In this context, we propose a subsequent study with the analysis of the penetration of electric vehicles in the Ecuadorian market, based on the international trends and the technological advances. At the beginning, the electric vehicles will require incentives to be competitive, as well as the development of an infrastructure in Ecuador to guarantee its commercialization. The use of electrical surpluses in the transportation sector implies reductions in fuel imports, freeing up economic resources for future power expansion.

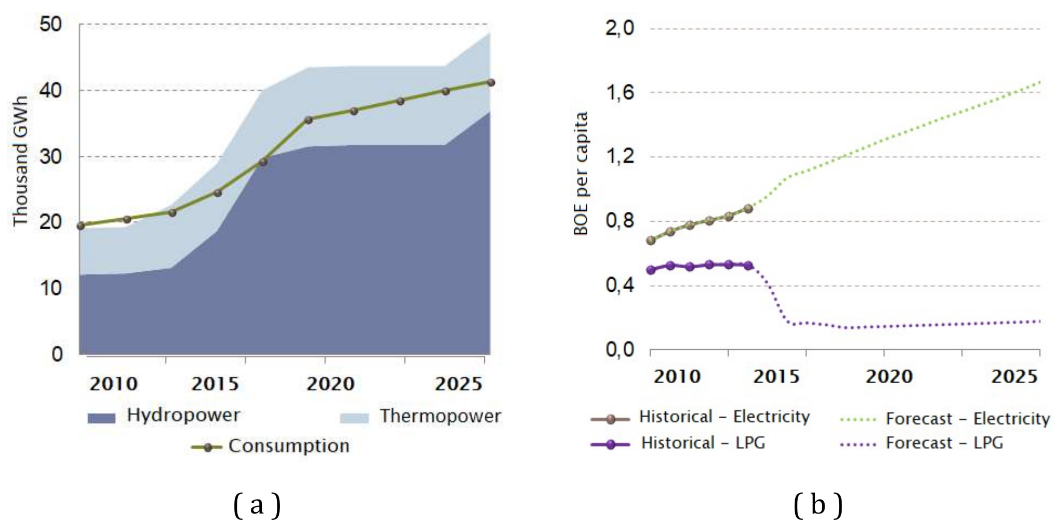


Figure 50 NDC implications: (a) power generation and (b) household consumption

NDC scenario shows that the electricity generation in 2030 is estimated to be 3.25-fold generation in 2010. This availability is due to the execution of all hydroelectric and thermoelectric plans. It will not have idle capacity in the electric system, as it will be linked to an increase in electricity consumption in the residential sector (Figure 50b). Since 2017, there is a larger share of hydroelectric power generation while the thermoelectric generation have not a significant expansion.

Figure 50b shows that the PEC program implies significant LPG savings in the residential sector, which are estimated at 10.66 million barrels of LPG. In the case of non-implementation of the program, there shall be a 56% increase in LPG consumption by 2030. The PEC program implementation, the increase in electricity consumption would be in 91% of the households by 2030, taking the base year as a reference.

The PEC program implies a 61% reduction in LPG imports, the equivalent of 3.90 million BEP by 2025. Consequently, domestic LPG production would be close to satisfy the local LGP residential consumption. Considering the base year economic conditions, this initiative implies a reduction of US$388 million for the government budget. This reduction would be shared between final and intermediate consumption, but the increase in energy consumption electricity is estimated at US$ 1,262 million.

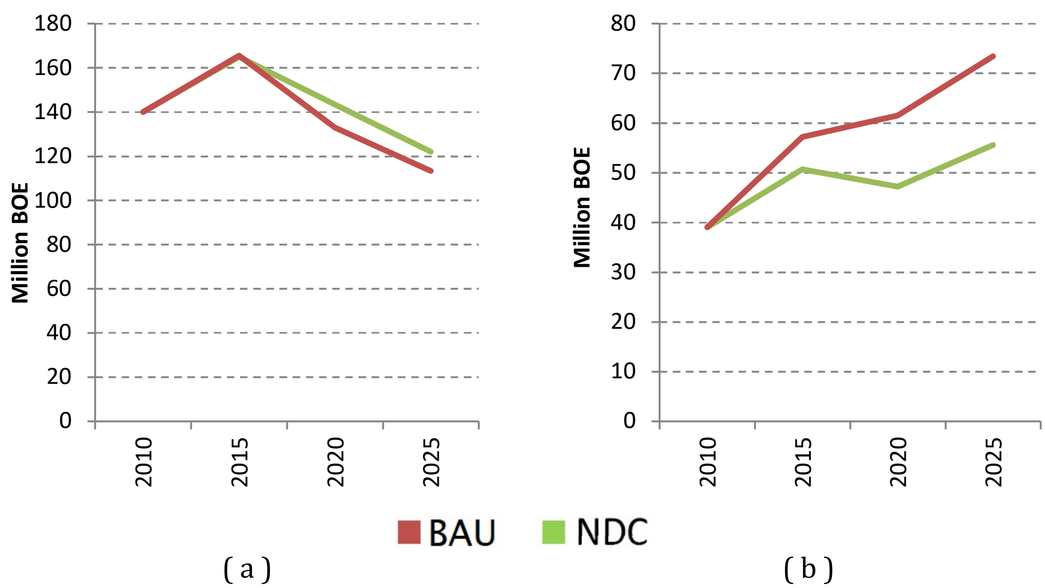
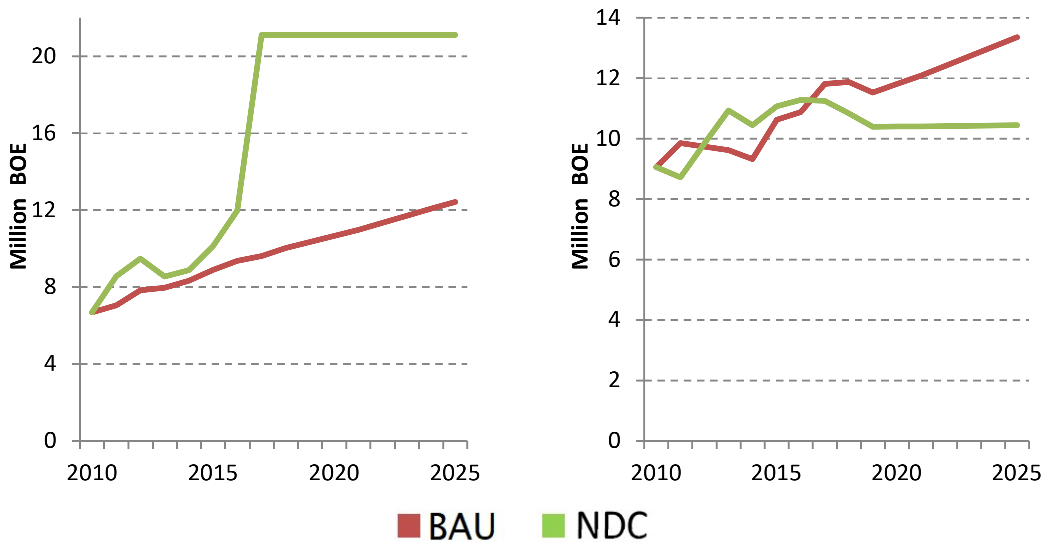


Figure 51 External market implication in scenarios: (a) exports and (b) imports

The NDC implementation has an external market implication that considers the dependence of crude oil exports on the Ecuadorian economy. The external market implications are more accentuated in energy imports than energy exports. The reduced consumption of refined products will result in lower imports (reduced by 24.32% - see Figure 51a mainly of LGP and fossil fuels). This reduction implies US$1,072 million in savings for the government budget by 2025. The NDC scenario during the 2015 - 2020 period projects a significant reduction of imports. This is mainly associated with lower diesel imports of 25% compared to the BAU scenario. However, there is an increase in imports in late 2020 due to demand from automakers.

Due to NDC implementation, Ecuador will become self-sufficient in electricity, reducing imports to zero and generating surpluses for export to neighboring countries. In this context, the energy exports would increase by 7.63%. However, this does not mean a change in the export structure, since crude oil will continue to be the main export product, representing 78% (NDC) or 84% (BAU) of total exports.

Consequently, there are no changes in the crude oil requirements or in its export levels in both scenarios. The NDC does not interfere in the reduction of emissions related to oil activity, the opposite situation when compared to hydropower requirements, which would increase rapidly from 2014 to 2017, reaching 70% until 2025 (Figure 52a).



(a) (b)

Figure 52 Primary requirements in scenarios: (a) hydropower and (b) natural gas

Figure 52b shows that the natural gas requirements from 2012 to 2016 would increase in the NDC scenario due to use of natural gas associated in the power generation. The scenario projects a decrease in its requirements by 22% from 2017 to 2025. These reductions are not related to a lower productivity or imports, but rather are due to the use of gas that is now flared off.

In the context of the first question proposed, the NDC guarantees a lower GHG emission due to the reduction in fossil fuel consumption as well as the use of less polluting sources. The transformation efficiency is increase and final consumption is reduced. However, there is a high concentration on hydropower expansion, which implies a high investment and hydrological dependence.

In addition, the oil horizon for both scenarios is not favorable. There is an average oil self-sufficiency of 15 years from 2025, assuming that new reserves are not incorporated. A refinery matrix change is necessary to increase local production of oil products, resulting in lower oil exports. Nevertheless, the new refinery capacity guarantees a reduction of oil product imports, as well as a surplus of gasoline and diesel available for local consumption or regional exports.

Ecuador is in a high-risk situation related to oil reserves and should apply an energy transition before 2030 or create an effort to discover new reserves by 2025 to avoid reserve's exhaustion. This condition indicates a need to evaluate NDC initiatives, allowing for an appropriate use of resources in productive sectors and a decreased allocation of energy resources to consumer sectors through energy efficiency policies.

Another alternative would be the change in the final consumption matrix, which is based on the existing biological resource. Sources of bio-based energy can be used for the residential or transportation sector.

5.2.3. Economic Implications

The NDC implementation projects an increase of 38.9% in GDP comparison with the base year, equivalent to US$ 27.07 billion in nominal terms, a real increase rate of 2.2%. This GDP growth is consistent with the historical average, which is around 3% a year. The NDC scenario will cause a 2.40% reduction in the unemployment rate and a decrease of 18.65% in the price index, so, the NDC initiatives are not counterproductive regarding for economic growth. This conclusion supported by the results of the main macroeconomic variables, answering our second research question.

The BAU scenario implies an unemployment rate reduction of 31.56%, while the NDC scenario implies a reduction of 28.66%. Both scenarios have favorable results for this indicator, but the BAU has more favorable conditions. Both scenarios guarantee a reduction in the price index of 20.16% and 18.65% for the BAU and NDC scenarios, respectively.

The BAU scenario implies GDP growth of 37.51% in comparison with the base year, a monetary value equivalent of US$95.64 billion and GHG emission of 53,150 $GgCO_{2-eq}$. The NDC implementation implies GDP of US$96.63 billion, a value 1.03% higher than the BAU scenario and a GHG reduction of 7,396 $GgCO_{2-eq}$. Therefore, the NDC would imply economic growth linked to a reduction in GHG, which enables compliance with environmental agreements along with appropriate economic results.

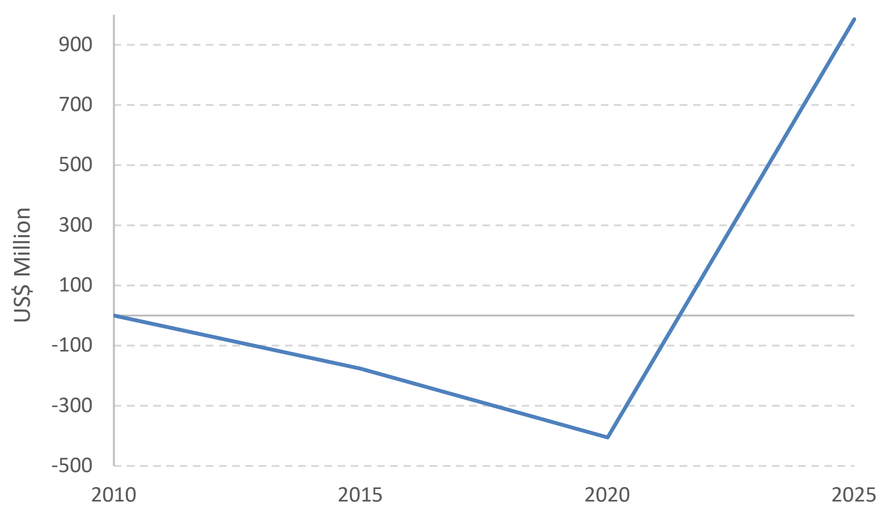


Figure 53 GDP variations between scenarios NDC and BAU

During the first years of implementation, there is a gradual reduction in GDP compared to trend conditions during the first years of it implementation, a period that extends until 2020 with a reduction of 0.4% compared to the BAU scenario (Figure 53). This behavior is explained by reductions in the households and government consumptions. However, after 2020 there is an immediate rebound in growth, reaching US$ 985 million in 2025, equivalent to 1.03% compared to the trend conditions, mainly the result of the significant increases in GFCF, so an implementation period is evident, involving investment and transition. Therefore, the challenge is to maintain these growth levels by diversifying energy consumption.

Table 12 Variations of production factors in the scenarios in 2025

Variables	BAU		NDC	
	Variation	Annual	Variation	Annual
GDP	37.5%	2.2%	38.9%	2.2%
Capital Supply	55.3%	3.0%	48.0%	2.6%
Labor Supply	28.0%	1.7%	28.0%	1.7%

The capital supply in the NDC scenario (55.3%) is lower than in the BAU scenario (48%). This means that the investment level necessary to achieve the NDC objectives is lower than the trend growth levels. In fact, to obtain the same levels of economic (GDP) growth between scenarios, the investment levels in the NDC scenario are less intensive than in BAU scenario (Table 12). In other words, the economy requires less effort to generate wealth as a result energy efficiency improvement.

The actions of the Ecuadorian NDC in the energy sector have positive impacts on the country's economic growth. This is the main hypothesis of this study, which is based upon the positive results of the main macroeconomic indicators and the answer top the second question proposed in this study. The results between the BAU and NDC scenarios are compared to determine the main affected and benefited sectors, to answer our third research question of the study.

Aggregate demand

There are equitable increases in the aggregate demand elements compared to the base year, so, the NDC implementation does not change the demand outlook. The most representative variation is the government consumption due to energy program investments. The GFCF increases are concentrated in the building sector (at 64%). This is due to the cost of services and raw materials to build hydropower plants. Plastic products and basic chemistry sectors will have reductions in their investment levels (GFCF) due to the lower consumption of fossil products.

NDC implementation is associated with increased household consumption of 37.57% compared to the base year, equivalent to US$ 16 billion, without changes in the consumption structure, but with increases in certain sectors. The consumption levels of agricultural products and processed food increases by 18.97% and 20.16%, respectively. Hence, households can purchase more processed foods, leading to an increase in consumption in the trade sector of 41.97%. There will be an increase of consumption in the transportation sector of 61.89%, because of the greater flow of manufactured goods.

In the NDC scenario, the household consumption will be less concentrated, meaning a more equitable consumption pattern, with few variations with respect to the base year. The main sectors are trade (15%), food industry (14%) and transportation (10%). The first one is a structural response, because trade is the major economic sector, with high productive chains. The second one varies due to the destination of household income to supply food or more manufactured products. The last sector represents the connection between products and consumers. The increased demand for transportation is consistent with historical consumer behavior, in which part of household income is allocated to purchase vehicles and fuel. It is important to avoid a rebound effect in energy consumption, as it opens the opportunity for electric mobility using power surpluses.

Table 13 Aggregate demand in the BAU and NDC scenarios in 2025

Expenditures	BAU scenario (US$ Million)	NDC scenario (US$ Million)	Variation
Household consumption	58,854	58,758	-0.16%
GFCF	23,652	24,490	3.54%
Government consumption	12,791	12,724	-0.52%
Exports	26,080	24,686	-5.34%
Imports	29,666	27,956	-5.76%
Stock variation	3,931	3,924	-0.17%

As seem in Table 13, not all elements of aggregate demand are benefited by GHG reduction policies. Household and government consumptions show slight growth compared to baseline conditions (BAU scenario), while the GFCF increases by 3.54% due to high investment levels. The main implications are in the external market, where there is a generalized decrease of imports and exports in comparison with the BAU scenario. The first case is due to the reduction of domestic consumption of refined oil products, representing 20.91% of the total imports in the BAU scenario. The NDC scenario reduces exports by US$1,393 million, the equivalent of 5.34%, mainly affecting the agriculture and food industries, whose exports decrease in the NDC conditions.

From 2010 to 2020, there is a reduction in household consumption in the NDC scenario compared to the BAU scenario, reducing the consumption by US$ 563 million by 2020, equivalent to 1.04%. Although the NDC scenario implies an increase in household consumption by 2025, reducing the scenario gap to US$95 million, during the analysis period the BAU scenario envisions higher consumption of households, so the implementation of the NDC would imply a reduction in the consumption of households with respect to the trend conditions. During the first years, there is minimum difference in government consumption between scenarios This, would be a planning period because NDC projects require significant investments in infrastructure, starting with design. According to the figure, the NDC scenario would have a decrease of US$ 200 million in government consumption by 2020 in comparison with the BAU scenario, equivalent to 1.70%. However, this difference is significantly lower in 2025, with a peak in public spending and its subsequent stabilization.

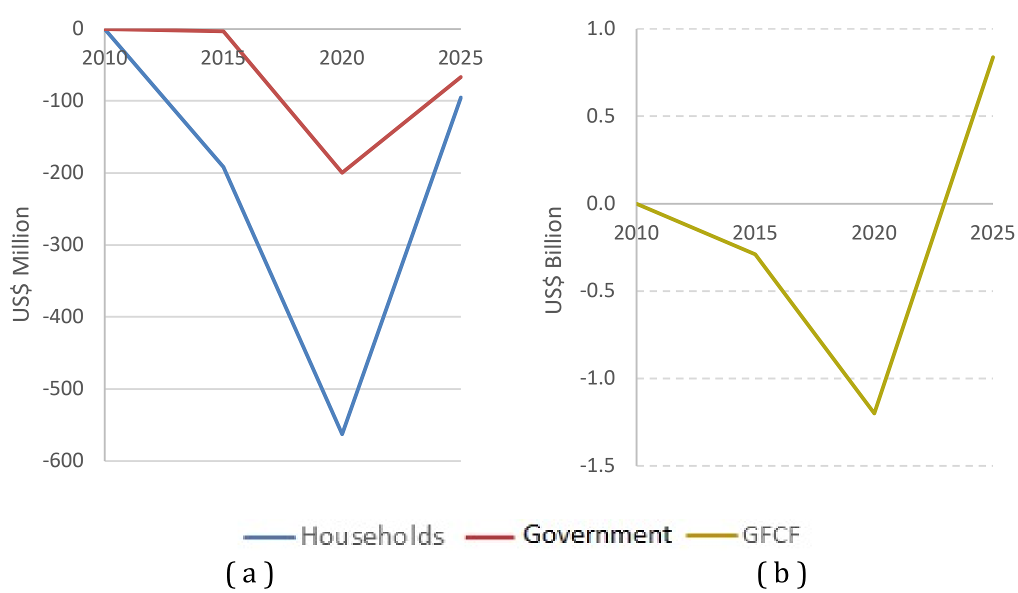


Figure 54 Variations between scenarios NDC and BAU scenarios in: (a) consumption levels and (b) GFCG

Throughout the analysis period, the NDC scenario implies higher government consumption compared to the BAU scenario, so the NDC implementation would imply a general increase in government consumption compared to trend conditions. During the period from 2015 to 2025, there are similar results between government and household consumption (Figure 54), because of the prioritization in investments required for the NDC initiatives. Likewise, there is a gradual increase in income tax revenues in the NDC scenario compared to the BAU scenario, reaching stabilization from 2020 onwards.

From 2010 to 2015, NDC implementation implies a gradual reduction of GCCF compared to the BUA scenario, a tendency which extends until 2020, with a reduction of 5.4%, equivalent to US$ 1.1 billion. After this period, there is an immediate rebound in growth, reaching US$ 838 million in 2025, equivalent to 3.50% compared to the trend conditions, because of the increase investments investment. So, the GFCF would be characterized in two periods: transition and implementation. The first, without major variations compared to trend conditions and the second with immediate increases.

Between the analyzed scenarios, there is a reduction of US$95 million in household consumption, the equivalent of 0.16%. The main reductions occur in the sectors of agriculture and processed food. There are also slight reductions in tertiary sectors, such as commerce and finance. However, secondary sectors (such as pulp/paper, plastics, and metallurgy) will increase consumption, probably due to the lower electricity costs. Households would also increase their electricity consumption by 18.38%, the equivalent of US$161 million. Consumption of oil products would increase 9.02%, with an opportunity to prioritize the consumption of locally produced fuels, reducing imports of refined products.

External market

In the external market, NDC initiatives imply an import increase of 24.02%, where fossil fuel and building sectors represent 16.91% and 12.04% compared to 2010, respectively. The total amount of exports will increase by 33.89% in comparation with the base year, the share of oil exports will decline from 48.55% to 28.65%. This happens not only because of the higher electricity, but also to growth of other sectors, such as food industries and farming. There would be significant variations in external market conditions due to the greater availability of energy resources.

The total amount of exports will increase in US$ 6.25 billion in comparison with the base year. The electricity exports will increase by 1,151%. In monetary terms, the increases range from US$13 to US$167 million due to NDC implementation. Despite this significant increase, the crude oil sector would continue being the main export sector. However, as result of the reduction in crude oil reserves (Espinoza et al., 2019), exports will decrease by 21%, an equivalent of US$ 1.88 billion.

The opposite situation occurs in the farming and food industry sectors, which will increase their exports by 92.80% and 93.90%, respectively, in the NDC scenario. These are equivalent of US$5 billion, with greater importance in the Ecuadorian export structure. Most exports are concentrated in a few sectors, so the economy is highly vulnerable to external market changes. This condition also exists in the base year scenario, but the NDC implementation will not guarantee a change on the export mix. Due to limitations in refinery capacity and oil reserves, oil refining and basic chemistry sectors will increase imports by 44% and 55% respectively, the equivalent of US$1.6 billion.

Electricity surplus due to NDC implementation encourages the external market for the following sectors: electrical machinery, and transport machinery. Both of them are related to the greater efficiency of electrically powered vehicles in relation to internal combustion vehicles, implying improvements in productivity. Despite high exports and lower imports, there will be a trade deficit of US$ 3.2 billion, but with a deficit reduction of 25.51% in comparison with the base year. NDC implementation would improve the trade balance, but its initiatives are not enough to achieve a positive trade balance. So, there would no structural changes in the Ecuadorian external market.

Despite the large increase in the electric energy exports, the surplus depends on technical aspects and market availability. Electricity is a secondary source of energy since its storage and transmission require the installation of extra facilities. While batteries only allow electricity to be stored in small quantities, other indirect methods, such as those involving transformation processes, allow the storage of large amounts. The electricity transmission would entail the construction of a costly infrastructure, including transmission lines to external markets, a constraint to international market availability. Considering the technical restrictions, the logical markets would be the bordering countries, i.e., Peru and Colombia. However, these countries currently do not have electricity deficits and their energy planning programs do not envision significant energy import scenarios for the next 10 years. Therefore, the feasibility of Ecuadorian exports depends on commercial agreements in the region.

There will be reduced export of crude oil exports and refined products, due to reduced consumption and production of hydrocarbons. This is the desired effect from implementation of the NDC, which guarantees GHG emission reductions. Oil exports are the main source of income of the Ecuadorian economy, so a scheme that guarantees the maintenance of the same export levels is needed.

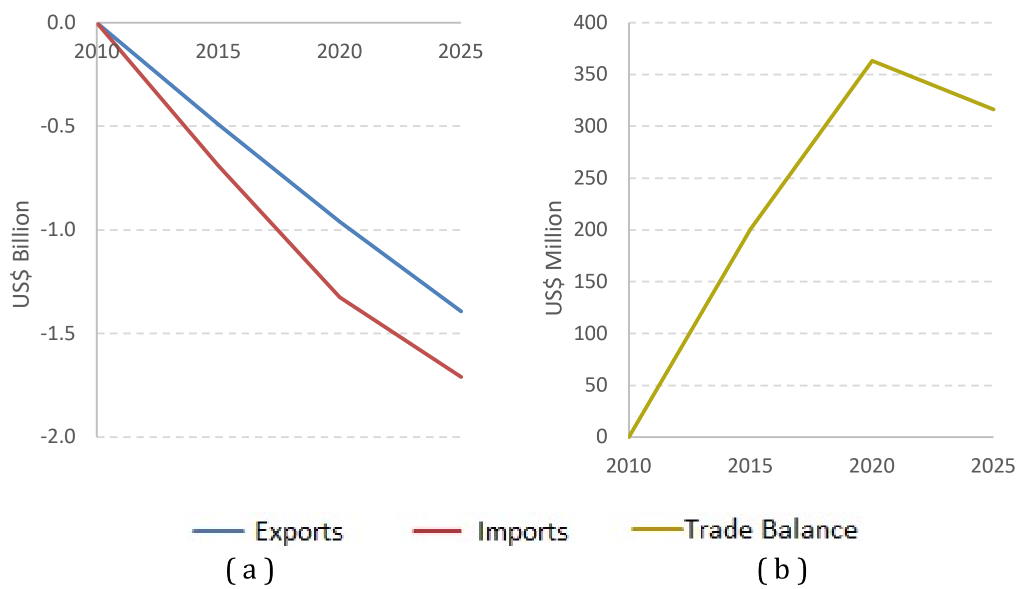


Figure 55 Variations between scenarios NDC and BAU in: (a) external market and (b) trade balance

Figure 55 shows continuous import and export reductions with respect to trend conditions. Despite the significant increase in electric power exports in the NCD scenario, exports would decline at an annual rate of 3.87% due to the productive chain of fossil fuels sectors, mainly affecting agriculture and the food industry, which concentrate 67.54% of this reduction. In fact, this last sector presents an increase of 62.51% in imports.

The NDC initiatives imply a reduction in total imports at an annual rate of 4.45%, that is, there is greater reduction of imports than exports with respect to the BAU scenario. In fact, the 78.65% reductions with respect to the BAU scenario are focused on services and supplies for the oil extraction and refining industry, because of the reduced consumption of fossil fuels.

The variations in the external sector have implications for the trade balance, which is negative for both scenarios throughout the analysis period. This is a frequent condition in the Ecuadorian economy as a result of its status as an importer of goods with high added value and an exporter of commodities. However, the NDC would imply an improvement of US$363 million in the trade balance with respect to the BAU scenario, because of the greater reduction in imports. During the analysis period, in the NDC scenario the trade balance is negative, which implies positive external savings, so the external sector would be financing domestic consumption. However, during the period from 2020 to 2025 in the same scenario, there is stabilization of the trade balance, with a variation of only -0.10%, so that in this period there is a reduction in external savings as a result of the NDC initiatives.

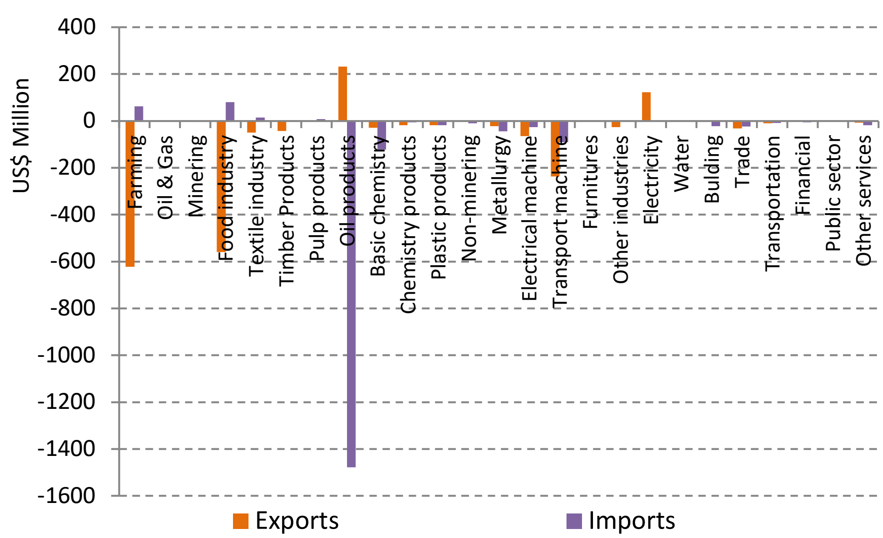


Figure 56 Variations of exports and imports between scenarios NDC and BAU in 2025

Electricity would be the most relevant export product, with an increase of 268% in comparison with the BAU scenario. In monetary terms, this increase is the equivalent of US$ 121 million. The oil products sector presents an increase of 30% (US$230 million), mainly due to the surplus of fuel oil for export. Despite the significant increases in exportation of electricity and oil products, the NDC and BAU scenarios have similar export structure results for 2025 (Figure 57a). In both, 70% of exports are concentrated in the crude oil, farming and food industry sectors. So, there would be no change in the economy's export structure.

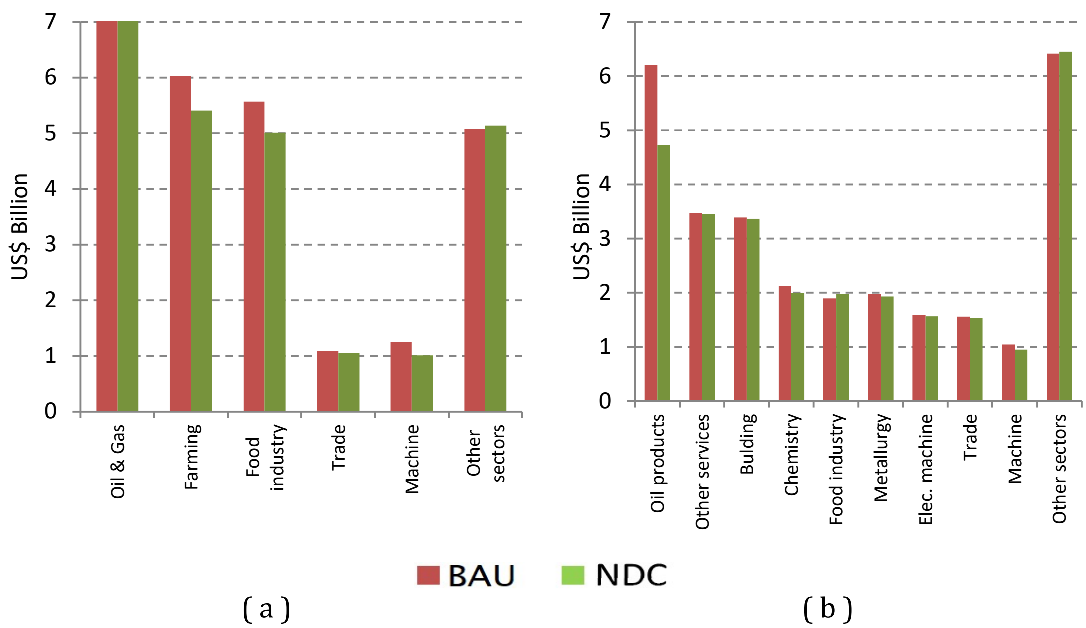


Figure 57 External market by scenario in 2025: (a) exports and (b) imports

Several sectors reduce their imports in the NDC scenario, in which there is a total reduction of import of US$ 1,709 million, concentrated in refined oil products and basic chemicals. As seen in Figure 57b, the main NDC implication is the lower importation of oil products imports, which is 31% lower than in the BAU scenario, an equivalent of US$ 1,477 million. However, farming, food and textile industries will increase their imports by 7%, 4% and 3%, respectively (US$156 million all told). This discourages increased domestic production by these sectors.

Electricity exports are also necessary to guarantee appropriate growth and use of electricity surplus as time passes. It is necessary to guarantee available external markets to export surpluses, or increase domestic consumption, which implies a decrease of electricity prices. Productive sectors could use electrical technologies (such as induction furnaces and electric cargo transport vehicles), which opens the possibility for irrational use of electrical energy due to low market prices.

Tax revenues

Annual tax revenue in the NDC scenario is less than in the BAU scenario by US$ 48 million, the equivalent of 1.3%. This means there would be no significant impact on the Ecuadorian fiscal situation. As shown in Figure 58, this reduction is concentrated in secondary sectors, such as processed food, basic chemicals, and transport machines. Additionally, there would be reductions of 21% and 29% in consumption and income tax revenue, respectively. The reductions in the electricity sector are equivalent to US$ 116 million due to subsidies.

In both conditions, the subsidies in the electricity sector imply reductions in tax revenue, and a tariff revision would be desirable to increase revenues. Another option is to maintain the subsidy but guarantee incentives to household consumption, while allocating consumption in other sectors. Increased power generation implies more revenue from production tax, the equivalent of US$519,000. This represents 25.34% of the total amount of taxes collected yearly. In addition, there is a homogeneous increase in tax revenue from service sectors, except the transportation sector, which will produce 6% lower income tax revenue, probably due to the lower investments in this sector.

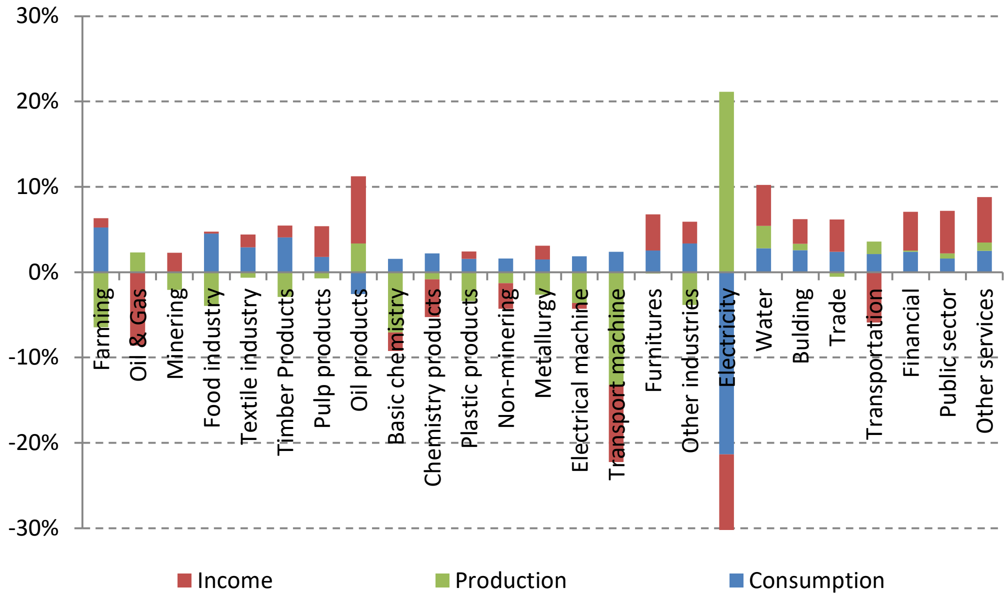


Figure 58 Variation in tax revenue between scenarios NDC and BAU in 2025

As a consequence of the reduction in tax revenue, there is a decrease in government income and expenditures. The NDC scenario presents a reduction of US$66 million in comparison with the BAU scenario, the equivalent of 0.52%. This is relevant only for the government expenditures, but not for other sectors. In the NDC scenario, there is an increase of taxes collected compared to the base year (2010), with some exceptions. So, the government spending increases by 9.64% (the equivalent of US$ 320 million), partly because the resources availability of tax revenue. The consumption tax continues to be the main category of tax revenue, accounting for 87.26% of the total collected, where the service sectors have the largest increases, such as trade, finance and public services; Nevertheless, transport machinery has the greatest increase of 31.16% related to investments in urban mobility and agricultural machinery.

Also, compared with the base year, income tax will reduce its share from 6.01% to 2.64%, due to reductions in taxes on income in the electricity sector due to NDC implementation. Despite an increase of electricity consumption of 16.57%, subsidies in this sector are counterproductive and imply higher government spending without a corresponding increase in revenues. A revision of tariff specifications in the sector would be necessary, taking advantage of the reduction in production costs. Another NDC collateral effect of subsidies is reflected in the transportation and oil refining sectors, where income taxes are reduced by 21.06% and 11.90%, respectively. This implies an increase of US$50 million in government spending on subsidized fuels. The NDC implementation should be linked to a consumer price policy to avoid inefficient uses of government resources.

However, the NDC implementation has positive implications in production tax revenues. Considering general revenue for all productive sectors, increases in production levels mean higher tax revenues. These increases are due to reduction in energy costs, such as oil products and electricity. The electricity sector will increase its tax revenue by 123%. In monetary terms, the transport and commerce sectors are more relevant, totaling US$30 million in revenues. Unlike other types of taxes, production taxes are not concentrated in a cluster of sectors but are more disseminated among different sectors.

Price variation

There is a price index reduction in both scenarios (BAU 20% and NDC 18%). So, the BAU scenario is more favorable than the NDC scenario an unfavorable condition of the NDC initiatives (Figure 59). Tertiary sectors have similar price reductions between scenarios and secondary ones have a wider variation in the reductions. Basic chemistry, pulp products, and metallurgy sectors are less favored with the NDC implementation.

Oil products have a price reduction of 95.72% and 35.02% for the BUA and NDC scenarios, respectively; this sector the least favored by the NDC. The BAU scenario implies an increase of 78.39% in electricity sector prices, while the NDC scenario implies a reduction of 3.87%. The first case is due to the use of imported or low-efficiency fossil fuels for power generation. The second is due to the use of hydropower, this is cheaper and more efficient.

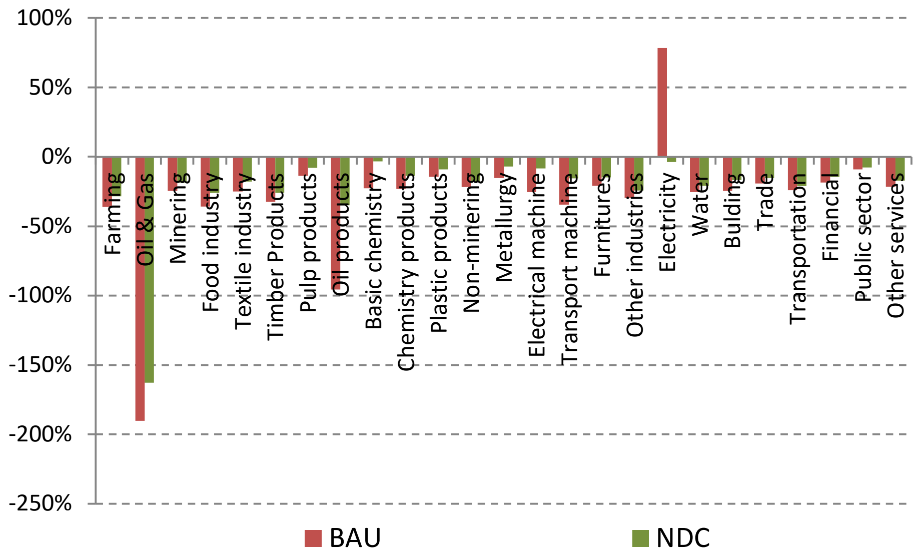


Figure 59 Price variations between scenarios in 2025

There is a general reduction in prices with respect to wages, reflected in 18.65% reduction in the price index. In the NDC scenario the final electricity price to consumers would be around US$ 0.05-0.06/kwh, a decrease of 33% in relation to current market prices. These competitive prices could allow local industry to generate greater added value, as well as lower cost to produce intermediate product of between 0.5% and 1%, but with price increases of public and financial services of 1.56% and 1.14%, respectively. Also, the cost of transportation would decrease by of 2.77%, due to more passenger transport modalities and the use of electricity. This would increase the purchasing power of households.

Productions factors

There is an increase in the capital supply, with disseminated effect on production factors among all the sectors for both scenarios. Transport machines have the largest increase in the BAU scenario, with 166.74%. The lesser increase in the NDC scenario is due to lower increase in this sector, which reflects lower use of fossil fuels.

The electricity sector has the largest increase in the NDC scenario with 145.30%, reflecting the impact of investments for electricity generation and more efficient energy consumption. There is an increase of capital and labor supply in the transport machines, basic chemicals and farming sectors in both scenarios. The tertiary sectors (trade, transportation, financial and public services) have similar increases of approximately 60% in both scenarios. These sectors would have only slight impacts on their investment levels due to NDC initiatives.

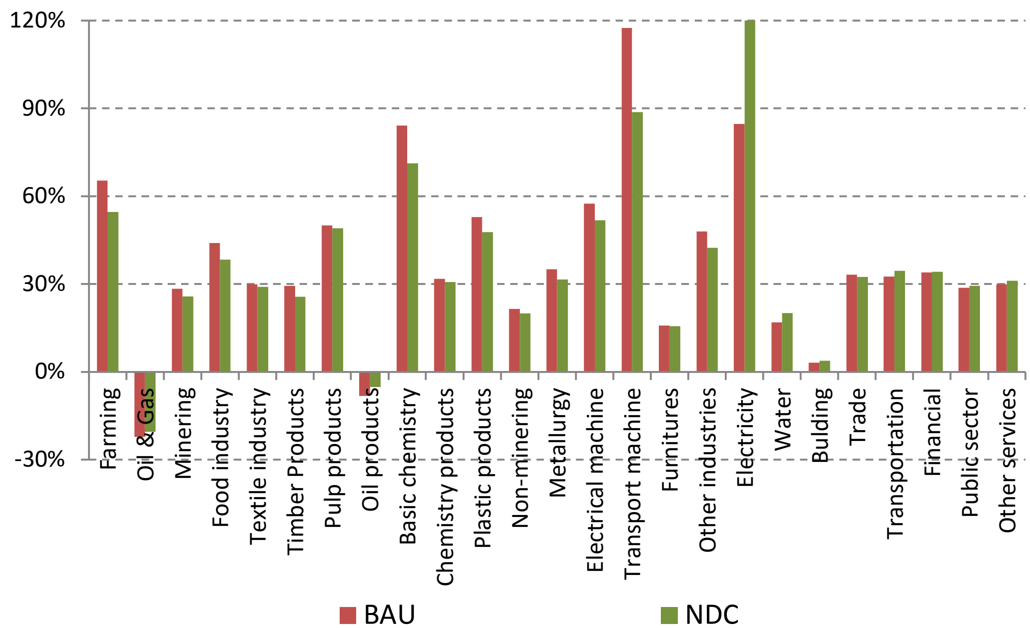


Figure 60 Labor supply variation between scenarios in 2025

As a result of lower oil reserves in both scenarios, there is a reduction in capital supply in the crude oil sector. This is more accentuated in the NDC scenario than the BAU scenario. A similar trend exists for the labor factor, with a reduction of 10.81% in the BAU scenario and 11.07% in the NDC scenario. There will be reduced employment in this sector, regardless of NDC implementation. It is thus necessary to define public policies to mitigate this situation. The oil products sector has capital supply increases and labor supply in both scenarios (with a greater incidence in the BAU scenario). The NDC implementation implies reductions in capital supply levels for the sectors related to fossil sources. At the same time, it implies a reduction of unemployment in these sectors, probably due to the migration of skilled labor to other technical sectors, such as electricity, water and construction.

Increased demand for production factors (capital and labor) is generalized in the sectors, except for the crude oil and oil products sectors, in which there would be decreases. There is an increase of 14.66% in the demand for capital in the oil refining sector, due to the increases in consumption in fossil-fuel-based transportation. This implies high investment levels to satisfy the growing demand. The main benefited sectors will be electricity and transport machinery, a predictable result due to the shift in consumption and production from fossil sources to low polluting sources.

At the same time, the pulp and paper sector would also benefit from the energy transition. Since it is an energy-intensive industry, competitive costs plus a significant cheaper supply of electricity would allow the use of more efficient machinery. It is advisable to propose transition strategies to direct job losses in the oil extraction and refining sectors towards the new jobs generated in other productive sectors, such as agroindustry and technology.

Service sectors have uniform growth, reflecting similar NDC implications among them, probably because of their lower dependence on the energy sectors. Despite the increase in tertiary sector prices, their capital and labor supply would also increase. The industrial sectors have dispersed growth, with more sensitive sectors in basic industry and electrical machinery. The construction sector demands more capital than labor, that, i.e., it is not a labor-intensive sector. It is a sector that would also demand higher skilled worker, due to technological advances in the first phases of the initiatives. This is also related to investment levels required by the construction of electrical infrastructure (designs and other services) both in the public and private spheres.

Nevertheless, with NDC implementation, crude oil consumption would decrease the most, by 71%. However, this sector has low household consumption, linked mainly to chemical and plastic products, with respective decreases in consumption of 11.39% and 7.21%. Thus, it is important to define policies for these sectors to avoid job losses or reduction of their investment levels, where the demand for labor and capital for crude oil extraction would decrease 11.07% and 20.38%, respectively.

In the model, the economy's savings are allocated to investment (Eq.12), so, the financing of the NDC initiatives would be covered by these resources. This would be mainly due to household and government savings, which in the NDC scenario would together increase by US$300 million, equivalent to an annual increase of 2% compared to the BAU scenario. The investment required for the NDC implementation is estimated at US$2.5 billion (Table 11), the hydroelectric power concentrate most of this investment. So, over a period of 8 years, the savings levels could finance these initiatives.

5.2.4. Summary of results

The Ecuadorian case provides evidence of economic growth and GHG emission reduction, as the result of using less polluting energy sources. However, we recognize that there would be no changes in the country's energy-productive structure. This means no changes in the levels of production and exports of crude oil. GHG reductions are a consequence of the reduction in fossil fuel consumption in the mid-term. Decreasing fuel imports, expanding domestic refining structure and/or making available a significant amount of fossil fuels for regional exports are all possible solutions.

Table 14 Index results by scenario in 2025

Index	BAU	NDC	Units
Final consumption	110	107	Millions of BOE
Household consumption	2.68	2.30	BOE per household
Consumption per *capita*	5.91	5.79	BOE per inhabitant
GHG per *capita*	2.86	2.46	$TNCO_2$ per inhabitant
Energy intensity	1.08	1.06	BOE per US$
GHG intensity	522	449	$kgCO_2$ per Thousand US$

According to the study´s results, we conclude that the **actions in the energy sector of the Ecuadorian NDC will have positive impacts on economic growth**. Therefore, the main hypothesis of this study is confirmed. This conclusion was reached considering implications in GDP variation, creation of jobs, price index variation and external market implications, as well as its adequacy to the country’s productive structure. In addition to these conventional macroeconomic results, we propose a specific energy-economy index between scenarios to evaluate the implications of Ecuadorian NDC to respond the main study´s questions (Table 14).

What will be the main affected and the main benefited sectors?

In the transformation processes, electricity generation is the main beneficiary with an increase of 23% in efficiency transformation and a reduction of 66% in primary inputs, as well as a reduction in electricity costs of 33% compared to trend conditions. This reduction is due to increases in electricity generation, where the excess is allocated to regional exports, increasing from US$ 13 to 167 million. The energy consumption per household would decrease by 14.18% in the NDC scenario, while GHG per capita would fall by 14.98% (Table 14) and consumption per capita would be 2% lower. In the productive sectors, energy-intensive industries such as pulp & paper and metallurgy are benefited from cost reductions due to the use of more efficient technologies, reflecting the productive chains of the electrical machinery and transport machinery sectors, in which exports and domestic demand would increase by 61.36% and 5.62%, respectively.

Oil refining, sale of refined products and basic chemistry would be the harmed sectors because of the reduction in domestic consumption of refined products, such as: LPG, diesel and gasoline. These sectors' internal consumption would decrease by 9.02%, and the majority of the job losses is concentrated in these sectors.

What will be the implications on the main macroeconomic variables?

The NDC implementation implies a 1.03% increase in GDP and 2.73% reduction in energy consumption by 2025 in comparison with trend conditions, as well as a reduction of 6,482 GgCO2 for the same year, equivalent to a 25.41% GHG reduction.

There is a reduction in unemployment of 4.25% in absolute terms, implying the creation of 77,000 new jobs in the economy as a whole by 2025 compared to the BAU scenario. This increase is concentrated in sectors related to electricity generation, infrastructure and machinery. Despite the price reduction of electricity, where the productive sectors are the main beneficiaries, there would not be a significant reduction in the price index. In fact, the trend conditions present a reduction of 1.51% in price index compared to the NDC scenario. However, there is an increase in tax revenues in the NDC scenario for 2025, where income tax collection would increase by US$232 million, 2.10% more than forecast in the BAU scenario.

Finally, to obtain similar growth levels between the scenarios, the NDC implementation would be less capital intensive than the BAU scenario, implying a reduction of US$ 3,133 million in the capital supply by 2025, equivalent to a reduction of 4.69% in comparison with the BAU scenario. Therefore, energy efficiency initiatives are favorable to economic growth.

Is the productive economic structure consistent with the NDC goals?

The NDC initiatives are appropriate for the productive economic structure. We propose the development of electrical infrastructure that allows the use of natural resources available in the country, mainly the use of renewable sources, besides greater energy efficiency. Hence, a transition towards greater domestic electricity consumption is evident, with an increase of 18.37% compared to the trend conditions for 2025.

The behaviors of producers and consumers are consistent with price variations in goods and services, so there is a disincentive in the fossil fuel sectors, which would reduce their production by 5.21% and their final consumption by 14.18%. In this respect the residential sector is the main contributor to reduction. Likewise, there is evidence of consistency in the results of indicators with historical values such as energy intensity and GHG intensity (Table 14), where the implementation of the NDC would imply reductions of 1.85% and 13.98% with respect to the BAU scenario, respectively.

For 2025, the NDC scenario is associated with energy intensity of 1.06 BOE per US$, i.e., generation of one unit of wealth requires consumption of 1.06 energy units. Furthermore, in this scenario the GHG intensity is calculated at 499 $kgCO_2$ per thousand US$, so the generation of wealth in the NDC scenario would imply lower GHG emissions than BAU scenario.

6. Conclusions

The Ecuadorian NDC initiatives in the energy sector are feasible and framed in the country's economic-productive structure. GHG reduction strategies through the use of less polluting energy sources do not imply a reduction in GDP. Instead, there is a slight increase (when compared to trend conditions), so a less polluting transition is feasible.

The GHG reduction is concentrated in carbon dioxide emissions, accentuated since 2020 when new hydropower plants started operation. The energy transformation sector is the main contributor to GHG reduction. The household sector is the main beneficiary of energy savings due to more energy efficient cooking. There are reductions in the transportation sector, but these are marginal when considering the energy consumption levels in this sector. The productive sectors do not have significant energy savings.

Ecuador would benefit from both economic growth and GHG reduction. In fact, the NDC scenario is less intensive than the BAU scenario. In other words, the economy would require less effort to generate wealth as result of mitigation policies. However, it must be recognized that there would be no change in the country's productive and consumption structures. In fact, crude oil exports will continue as the main external financing source, while retailing will continue as the main consumption sector.

The macroeconomic impacts are concentrated in the external market. Electricity exports must guarantee the same income levels as crude oil exports. This will be a challenge, considering the physical limitations and low demand from bordering countries. Electricity surpluses must be guaranteed either for export or domestic consumption. Otherwise, NDC implementation will be counterproductive. The NDC initiatives guarantee reduced consumption of fossil fuels, decreasing their importation and need for local refining. This implies a significant amount of fossil fuels for regional exports, but possible GHG externalization is left open for debate.

Tax revenues in the energy sectors would be reduced by the decrease in fossil fuel consumption by the industrial and transportation sectors. Nevertheless, there would be a reduction in electricity costs for productive sector due to surplus power generation.

There also would be a general increase in the demand for production factors with transition from fossil fuels to electricity. The energy-intensive industries would benefit from more competitive costs, since the electricity supply would allow the use of more efficient machinery. Therefore, the NDC implementation would imply a migration of skilled labor to other technical sectors, such as electricity, water or construction.

The hybrid LEAP/CGE model applied to Ecuador was successful. It was possible to link the technical model with the macroeconomic one and their convergence was achieved by an adequate iterative process, using soft-link modeling based on energy-economic ratio and input-output variable connections. This study contributes to the first hybridization stage, which can continue with the hard-link stage and finally reach an integrated model.

An Ecuadorian productive transition is necessary, because the oil reserves are decreasing, which implies high economic impacts. The NDC is an opportunity where electricity generation is the focus to support technological industries or sectors, generating more added value.

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Appendix

Appendix A – Sectors and variable structures of GEM_EC

This section presents the variables and information to structure the CGE_EC, in the context of NDC conditions, as well as, the assumptions to LEAP model linking.

Table A. 1 Sectorial disaggregation

Sectorial Disaggregation	
Agricultural	*S1*
Oil & Gas	*S2*
Mining	*S3*
Foodstuffs	*S4*
Textile	*S5*
Wood & Timber	*S6*
Paper & Cellulose	*S7*
Refinery	*S8*
Plastic & Basic chemicals	*S9*
Chemicals products	*S10*
Rubber and plastic products	*S11*
Non-metallic	*S12*
Metallurgy	*S13*
Machinery & equipment	*S14*
Transport equipment	*S15*
Real estate	*S16*
Other industries	*S17*
Electricity	*S18*
Water services	*S19*
Construction	*S20*
Trade	*S21*
Transportation	*S22*
Financial services	*S23*
Public services	*S24*
Other services	*S25*

Table A. 2 Exogenous set of variables

Sector	Variable	Description
S_2	X_{d2}	Oil domestic production
	X_{dd2}	Oil supply
	E_2	Export of oil and similar
	I_2	Import of oil and similar
S_8	X_{d8}	Oil products domestic production
	X_{dd8}	Oil products supply
	E_8	Export of oil products
	I_8	Import of oil products
S_{18}	X_{d18}	Electricity domestic production
	X_{dd18}	Electricity supply
	E_{18}	Export of electricity
	I_{18}	Import of electricity

Table A. 3 Socio-Economic initial conditions

Socio-Economic		
Indicator	Value	Units
GDP	69.56	Billions of US$
Population	15	Millions of inhabitants
GDP per cápita	4,633	US$ per inhabitant
Households	4	Thousands of units
Urban	60%	
Rural	40%	
Electricity coverage	95%	
Workplaces	6.5	Jobs
Gross Value Add	64.50	Billions of US$
Final consumption	51.15	Billions of US$
Intermediate consumption	35.62	Billions of US$
Total exports	19.32	Billions of US$
Total imports	10.92	Billions of US$

Table A. 4 Energy-Environmental initial conditions

Energy - Environmental		
Oil Production	177	Millions of BOE
Refinery Supply	54	Millions of BOE
Final consumption	72	Millions of BOE
Consumption per cápita	4,81	BOE per inhabitants
Vehicles	1,172	Thousands of units
Passenger	797	Thousands of units
Cargo	334	Thousands of units
Ratio Sedan-SUV	1,98	
Energy intensity	1,04	BOE per US$
GHG emissions	33	Thousands of $GgCO_2$
GHG per cápita	2,25	$TNCO_2$ per inhabitant
GHG intensity	485	$kgCO_2$ per Thousand US$

Table A. 5 Final consumption variations

Sectors	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Agriculture	6%	16%	3%	10%	12%	3%	3%	0%	-3%	1%
Oil and mining	10%	-4%	78%	37%	-52%	9%	-1%	9%	-4%	3%
Animal industry	9%	9%	5%	11%	10%	1%	2%	2%	3%	-1%
Crop industry	6%	4%	7%	5%	5%	4%	1%	0%	-8%	0%
Manufacture	10%	15%	8%	12%	4%	1%	-2%	4%	2%	1%
Energy and transport	14%	7%	11%	8%	7%	16%	2%	8%	4%	2%
Construction	9%	12%	14%	5%	5%	6%	-2%	-3%	-3%	-3%
Services	12%	11%	9%	6%	8%	1%	-2%	5%	3%	1%
Public sector	11%	2%	22%	11%	-1%	38%	-3%	-13%	9%	-2%

Table A. 6 Intermediate consumption variations

Sectors	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Agriculture	7%	15%	5%	13%	11%	3%	-1%	6%	5%	3%
Oil and mining	7%	7%	10%	12%	2%	-13%	-1%	3%	11%	0%
Animal industry	8%	15%	6%	10%	12%	1%	2%	8%	2%	1%
Crop industry	8%	10%	6%	7%	5%	-4%	-2%	-2%	0%	-1%
Manufacture	13%	19%	8%	4%	4%	-8%	-7%	7%	6%	-3%
Energy and transport	6%	9%	10%	8%	10%	2%	-2%	3%	6%	-2%
Construction	9%	23%	19%	19%	9%	-2%	1%	-3%	2%	-4%
Services	10%	12%	9%	10%	8%	-1%	-4%	4%	8%	2%
Public sector	-6%	15%	28%	18%	12%	-11%	-21%	6%	13%	-3%

Table A. 7 Exogenous sectors

Crude oil - Sector 2
$X_{dd2} = \frac{X_{d_2}}{aT_2} \cdot \gamma_{X_{dd2}}^{\sigma_{T2}} \cdot p_{X_{dd2}}^{-\sigma_{T2}} \cdot \left[\gamma_{E_2}^{\sigma_{T2}} \cdot p_{E_2}^{1-\sigma_{T2}} + \gamma_{X_{dd2}}^{\sigma_{T2}} \cdot p_{X_{dd2}}^{1-\sigma_{T2}}\right]^{\sigma_{T_2}/1-\sigma_{T_2}}$
$E_2 = \frac{X_{d_2}}{aT_2} \cdot \gamma_{E_2}^{\sigma_{T2}} \cdot p_{E_2}^{-\sigma_{T2}} \cdot \left[\gamma_{E_2}^{\sigma_{T2}} \cdot p_{E_2}^{1-\sigma_{T2}} + \gamma_{X_{dd2}}^{\sigma_{T2}} \cdot p_{X_{dd2}}^{1-\sigma_{T2}}\right]^{\sigma_{T_2}/1-\sigma_{T_2}}$
$X_{dd2} = \frac{X_2}{aA_2} \cdot \gamma_{X_{dd2}}^{\sigma_{a2}} \cdot p_{X_{dd2}}^{-\sigma_{a2}} \cdot \left[\gamma_{M_2}^{\sigma_{a2}} \cdot p_{M_2}^{1-\sigma_{a2}} + \gamma_{X_{dd2}}^{\sigma_{a2}} \cdot p_{X_{dd2}}^{1-\sigma_{a2}}\right]^{\sigma_{a_2}/1-\sigma_{a_2}}$
$M_2 = \frac{X_2}{aA_2} \cdot \gamma_{M_2}^{\sigma_{a2}} \cdot p_{M_2}^{-\sigma_{a2}} \cdot \left[\gamma_{M_2}^{\sigma_{a2}} \cdot p_{M_2}^{1-\sigma_{a2}} + \gamma_{X_{dd2}}^{\sigma_{a2}} \cdot p_{X_{dd2}}^{1-\sigma_{a2}}\right]^{\sigma_{a_2}/1-\sigma_{a_2}}$
Refinery - Sector 8
$X_{dd8} = \frac{X_{d_8}}{aT_8} \cdot \gamma_{X_{dd8}}^{\sigma_{T8}} \cdot p_{X_{dd8}}^{-\sigma_{T8}} \cdot \left[\gamma_{E_8}^{\sigma_{T8}} \cdot p_{E_8}^{1-\sigma_{T8}} + \gamma_{X_{dd8}}^{\sigma_{T8}} \cdot p_{X_{dd8}}^{1-\sigma_{T8}}\right]^{\sigma_{T_8}/1-\sigma_{T_8}}$
$E_8 = \frac{X_{d_8}}{aT_8} \cdot \gamma_{E_8}^{\sigma_{T8}} \cdot p_{E_8}^{-\sigma_{T8}} \cdot \left[\gamma_{E_8}^{\sigma_{T8}} \cdot p_{E_8}^{1-\sigma_{T8}} + \gamma_{X_{dd8}}^{\sigma_{T8}} \cdot p_{X_{dd8}}^{1-\sigma_{T8}}\right]^{\sigma_{T_8}/1-\sigma_{T_8}}$
$X_{dd8} = \frac{X_8}{aA_8} \cdot \gamma_{X_{dd8}}^{\sigma_{a8}} \cdot p_{X_{dd8}}^{-\sigma_{a8}} \cdot \left[\gamma_{M_8}^{\sigma_{a8}} \cdot p_{M_8}^{1-\sigma_{a8}} + \gamma_{X_{dd8}}^{\sigma_{a8}} \cdot p_{X_{dd8}}^{1-\sigma_{a8}}\right]^{\sigma_{a_8}/1-\sigma_{a_8}}$
$M_8 = \frac{X_8}{aA_8} \cdot \gamma_{M_8}^{\sigma_{a8}} \cdot p_{M_8}^{-\sigma_{a8}} \cdot \left[\gamma_{M_8}^{\sigma_{a8}} \cdot p_{M_8}^{1-\sigma_{a8}} + \gamma_{X_{dd8}}^{\sigma_{a8}} \cdot p_{X_{dd8}}^{1-\sigma_{a8}}\right]^{\sigma_{a_8}/1-\sigma_{a_8}}$
Electricity – Sector 18
$X_{dd18} = \frac{X_{d_{18}}}{aT_{18}} \cdot \gamma_{X_{dd18}}^{\sigma_{T18}} \cdot p_{X_{dd18}}^{-\sigma_{T18}} \cdot \left[\gamma_{E_{18}}^{\sigma_{T18}} \cdot p_{E_{18}}^{1-\sigma_{T18}} + \gamma_{X_{dd18}}^{\sigma_{T18}} \cdot p_{X_{dd18}}^{1-\sigma_{T18}}\right]^{\sigma_{T_{18}}/1-\sigma_{T_{18}}}$
$E_{18} = \frac{X_{d_{18}}}{aT_{18}} \cdot \gamma_{E_{18}}^{\sigma_{T18}} \cdot p_{E_{18}}^{-\sigma_{T18}} \cdot \left[\gamma_{E_{18}}^{\sigma_{T18}} \cdot p_{E_{18}}^{1-\sigma_{T18}} + \gamma_{X_{dd18}}^{\sigma_{T18}} \cdot p_{X_{dd18}}^{1-\sigma_{T18}}\right]^{\sigma_{T_{18}}/1-\sigma_{T_{18}}}$
$X_{dd18} = \frac{X_{18}}{aA_{18}} \cdot \gamma_{X_{dd18}}^{\sigma_{a18}} \cdot p_{X_{dd18}}^{-\sigma_{a18}} \cdot \left[\gamma_{M_{18}}^{\sigma_{a18}} \cdot p_{M_{18}}^{1-\sigma_{a18}} + \gamma_{X_{dd18}}^{\sigma_{a18}} \cdot p_{X_{dd18}}^{1-\sigma_{a18}}\right]^{\sigma_{a_{18}}/1-\sigma_{a_{18}}}$
$M_{18} = \frac{X_{18}}{aA_{18}} \cdot \gamma_{M_{18}}^{\sigma_{a18}} \cdot p_{M_{18}}^{-\sigma_{a18}} \cdot \left[\gamma_{M_{18}}^{\sigma_{a18}} \cdot p_{M_{18}}^{1-\sigma_{a18}} + \gamma_{X_{dd18}}^{\sigma_{a18}} \cdot p_{X_{dd18}}^{1-\sigma_{a18}}\right]^{\sigma_{a_{18}}/1-\sigma_{a_{18}}}$

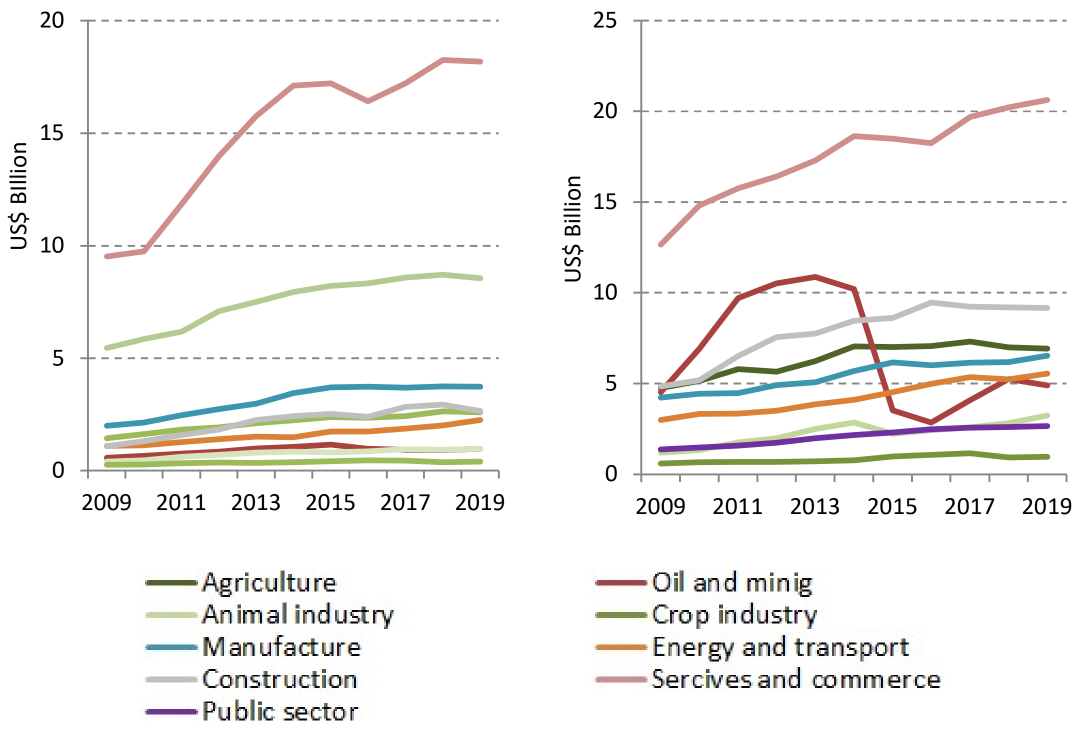
Table A. 8 Exogenous set of variables

The exogenous variables of the model are chosen based on the aims of the research

Exogenous variables
• Exchange rate (ER) • Household marginal propensity to save (pmp) • Other government transfers (OutTrf); • Government savings (Sgov); • Income tax rate (impR); • Household consumption taxes rate • Cobb Douglas exponents for Government consumption • Household subsistence consumption • Technical coefficients • Technology parameters • Import taxe rate (impC) • International price of imports (pM); • International price of exports (pE); • Cobb-Douglas exponents for Investments done by households, the government and sectors;

Table A. 9 Key assumptions by scenario in 2025

Parameters	BAU	NDC	Units
Demographics			
Population growth	1.55%	1.55%	%
Population	18	18	Millions of inhabitants
Household growth	2.19%	2.19%	%
Households	5,400	5,400	Thousands of houses
Urban	60%	60%	%
Rural	40%	40%	%
Electrification	95%	98%	%
Electric stoves	200	3,500	Thousands of units
Labor growth	1.4%	1.4%	%
Energy Sectors			
Oil crude production	155	155	Millions of BOE
Refinery Supply	54	54	Millions of BOE
Fuel oil consumption	10	5	Millions of BOE
Diesel oil consumption	14	3	Millions of BOE
Electricity Production	22.46	27.09	Thousands of GWh
Hydro capacity	24.42%	51.92%	%
Thermo capacity	75.58%	48.08%	%
Electrical voltage	230	500	kV
Gas Flaring	4.00	1.93	Millions of BOE
Gas Production Efficiency	60%	80%	%



(a) (b)

Figure A. 1 Historical remuneration of production factors (a) Labor and (b) Capital

Source: Prepared with data from BCE (2021)

Appendix B – Linking process in the MPC3e

This section presents the variables and information about the linking process between LEAP_EC and GEM_EC models, as well as, the errors in the energy sectors during the iteration process.

Table B. 1 MPC3e Linking process -errors in energy sectors

Itineration				
Variable	**First iteration**	**Second iteration**	**Third iteration**	**Fourth iteration**
Crude oil				
Production	0.002%	0.002%	0.002%	0.002%
Supply	0.002%	0.002%	0.002%	0.002%
Export	0.001%	0.001%	0.001%	0.001%
Import	-0.001%	-0.001%	-0.001%	-0.001%
Oil Products				
Production	0.002%	0.002%	0.002%	0.002%
Supply	0.004%	0.004%	0.004%	0.004%
Export	-4.044%	-0.042%	-0.042%	-0.042%
Import	0.032%	0.032%	0.032%	0.032%
Electricity				
Production	-0.003%	-0.003%	-0.003%	-0.003%
Supply	0.517%	0.517%	0.517%	0.517%
Export	-0.001%	-0.001%	-0.001%	-0.001%
Import	-0.596%	-0.596%	-0.596%	-0.596%

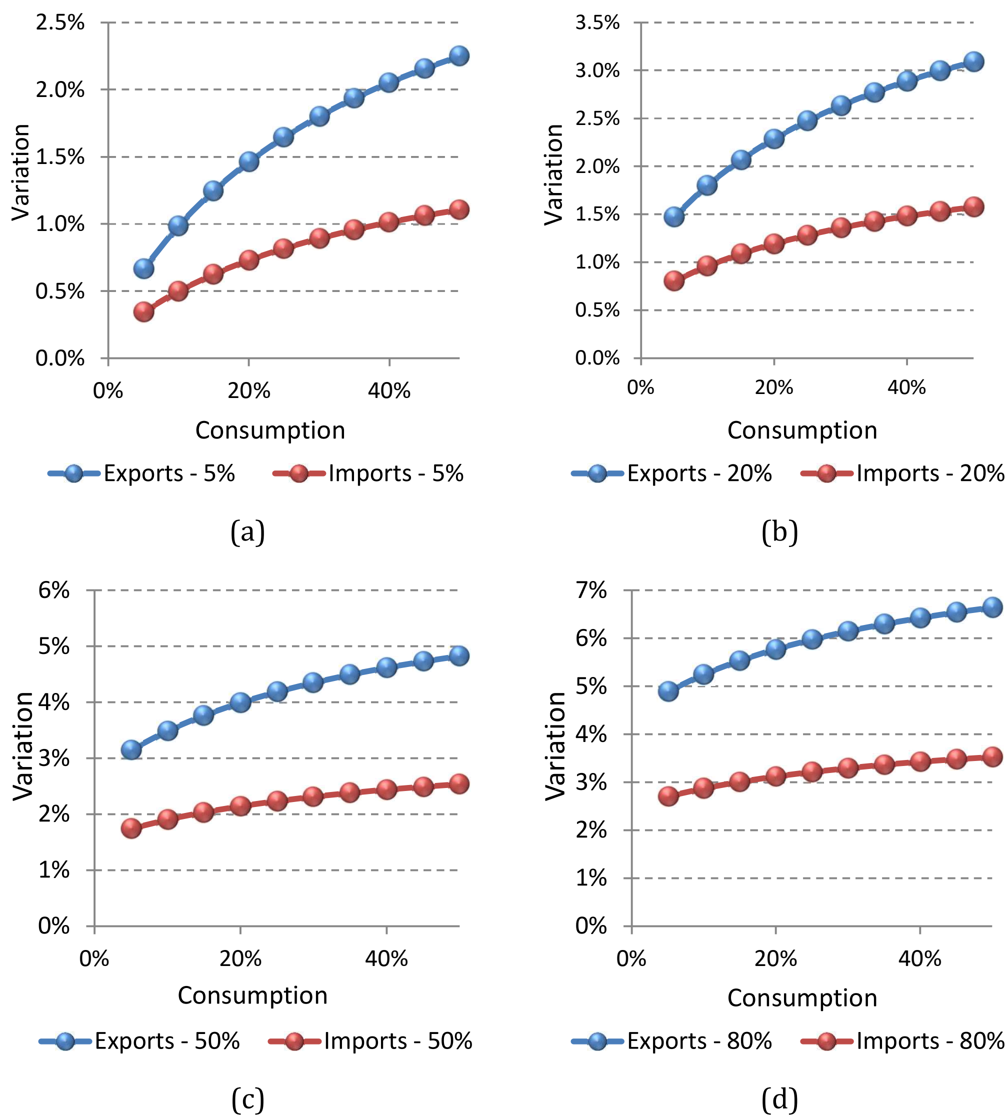


Figure B. 1 MPC3e execution in external market and electrical consumption increase of: (a) 5% (b) 20% (c) 50% and (d) 80%

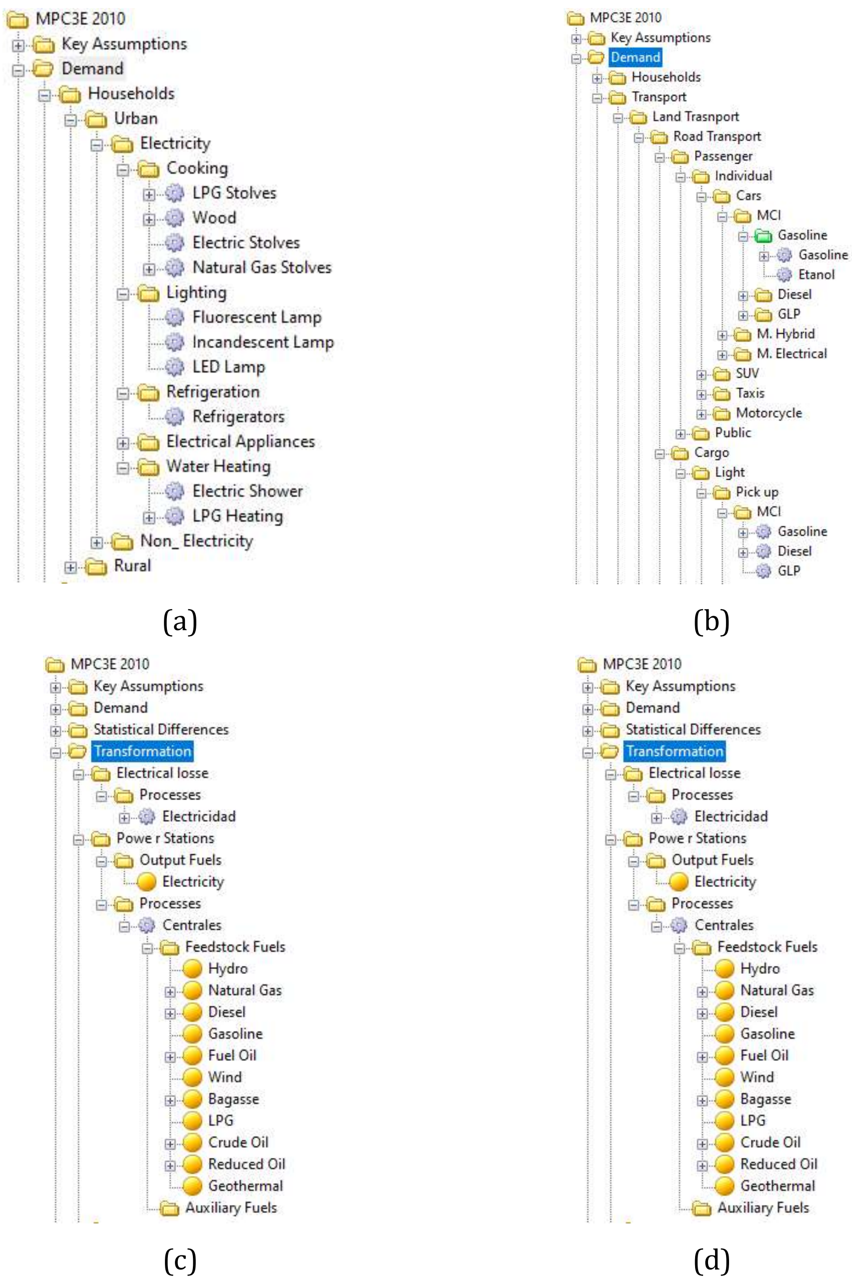


Figure B. 2 MPC3e's sectors for NDC assessment (LEAP_EC) : (a) households, (b) transport, (c) refineries and (d) electricity

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! Fechamento

! Setor Oil
exogenous M("s2") ;
exogenous E("s2") ;
exogenous Xd("s2") ;
exogenous Xdd("s2") ;

!Setor Fossil
exogenous M("s8") ;
exogenous E("s8") ;
exogenous Xd("s8") ;
exogenous Xdd("s8") ;


!Setor Elec
exogenous M("s18") ;
exogenous E("s18") ;
exogenous Xd("s18") ;
exogenous Xdd("s18") ;

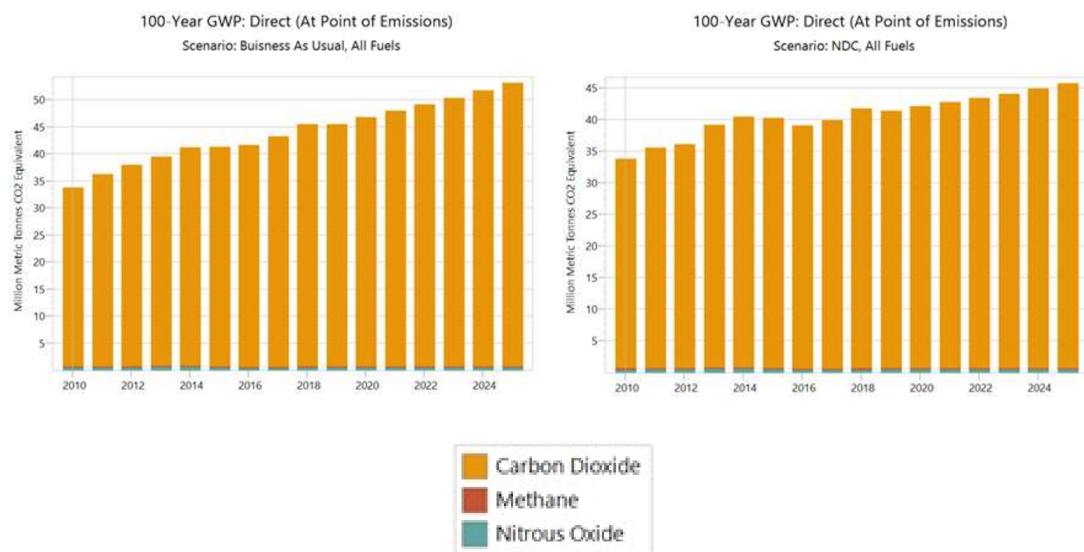
!Fatores Primários

exogenous Pfator("Trabalho") ;
exogenous Ofp("Trabalho") ;
```

Figure B. 3 MPC3e's sectors NDC assessment (CGE_EC): (a) households, (b) transport, (c) refineries and (d) electricity

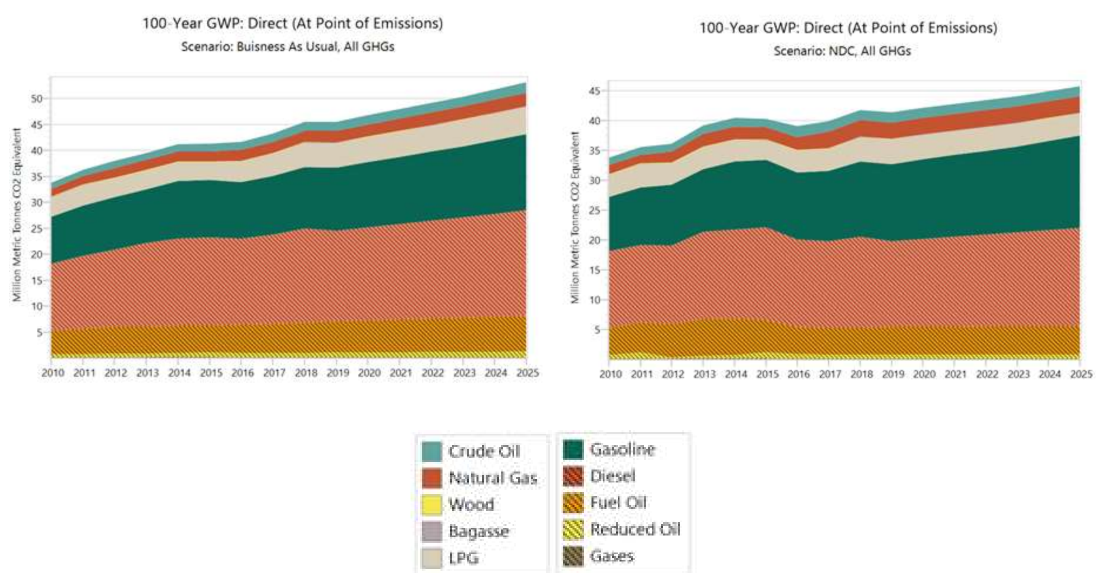
Appendix C – NDC impacts using MPC3e results

This section presents the results of MPC3e model applied to evaluate the NDC impacts in the Ecuadorian economy.



(a) (b)

Figure C. 1 Emissions desegregate by gases in the scenario (a) BAU and (b) NDC



(a) (b)

Figure C. 2 Emissions desegregate by fuels in the scenario (a) BAU and (b) NDC

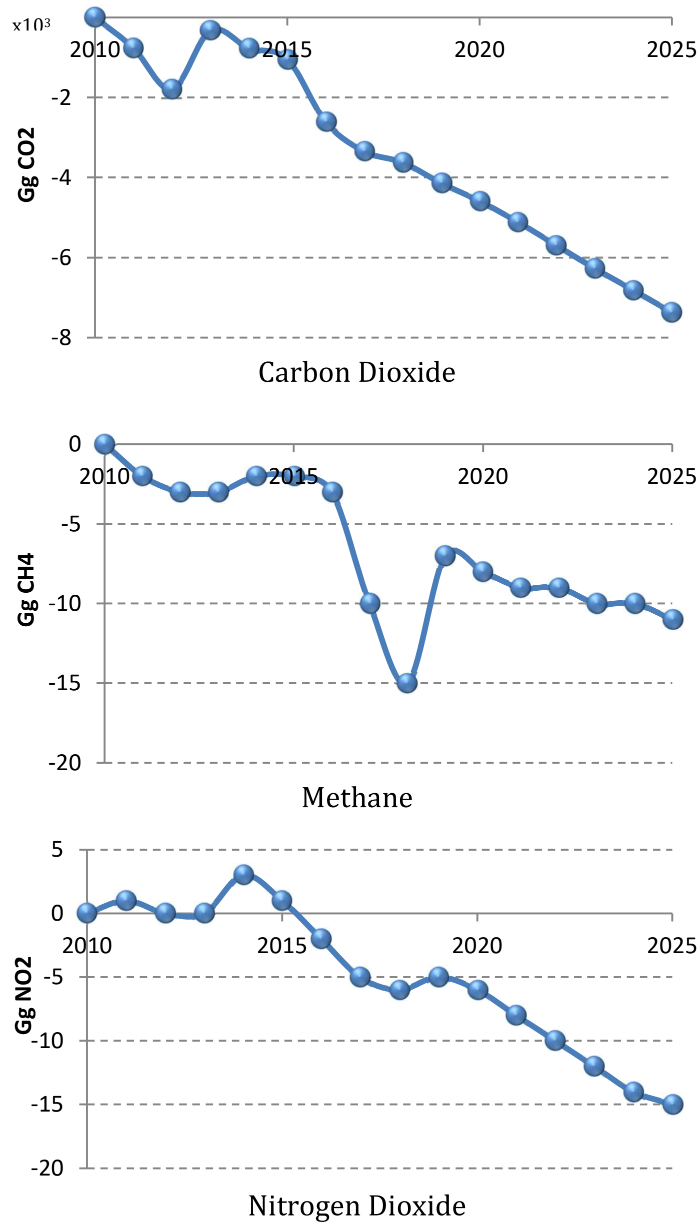


Figure C. 3 GHG reductions due to NDC implementation

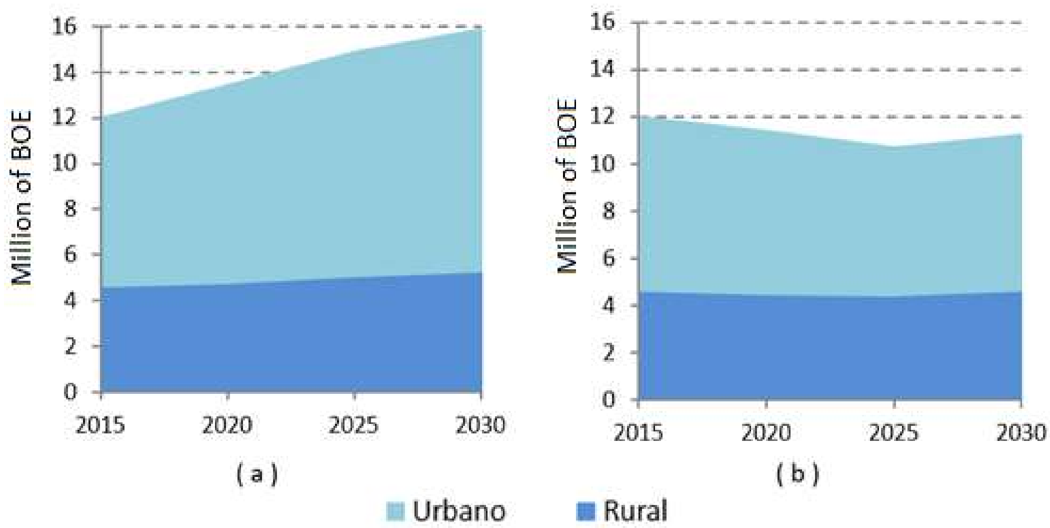


Figure C. 4 Beneficiaries of PEC Program in the scenario (a) BAU and (b) NDC

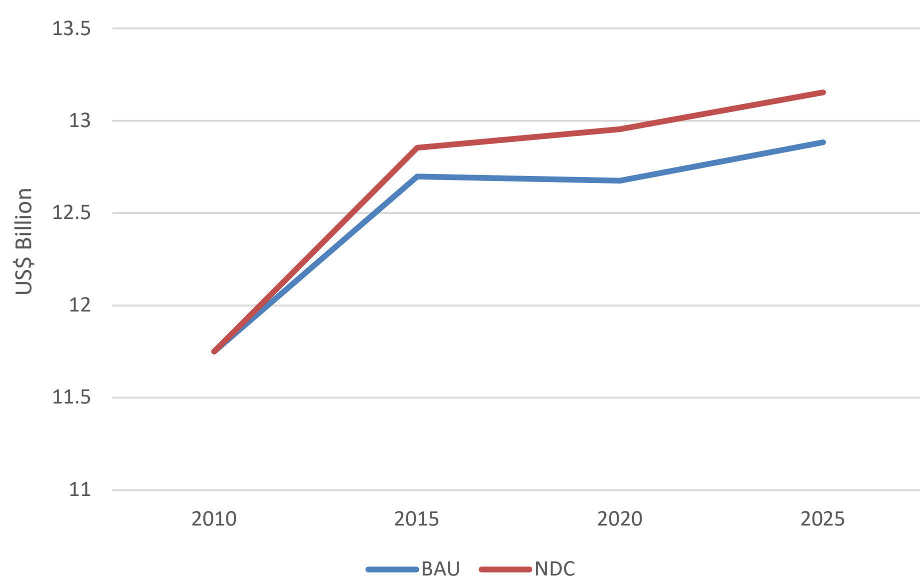


Figure C. 5 Households savings by scenario

Annex

This section presents additional information used to execute MOC3e modelling to evaluate the Ecuadorian NDC impacts.

Annex A

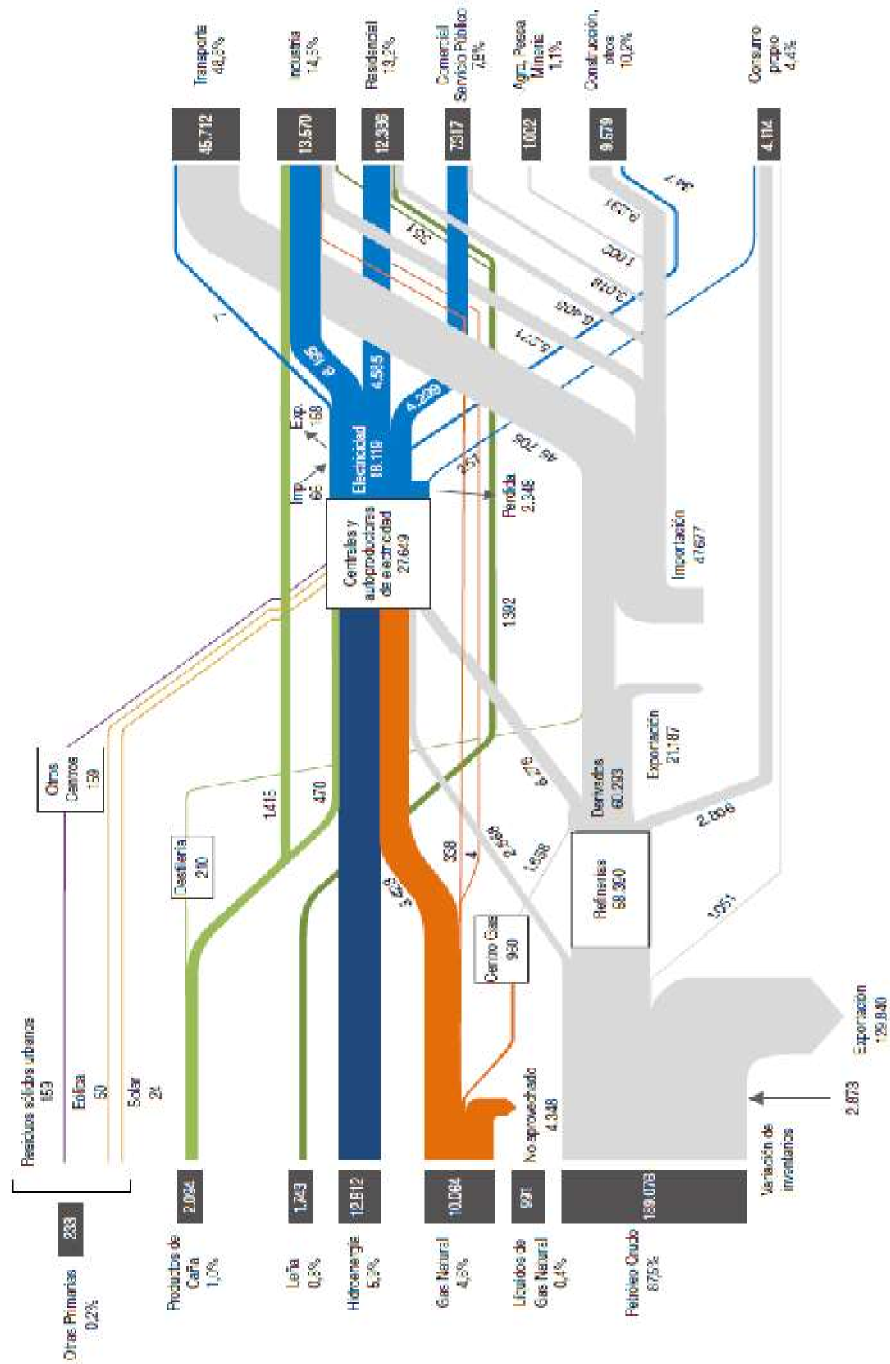


Figure D. 1 Sanky diagram - Energy balance 2015

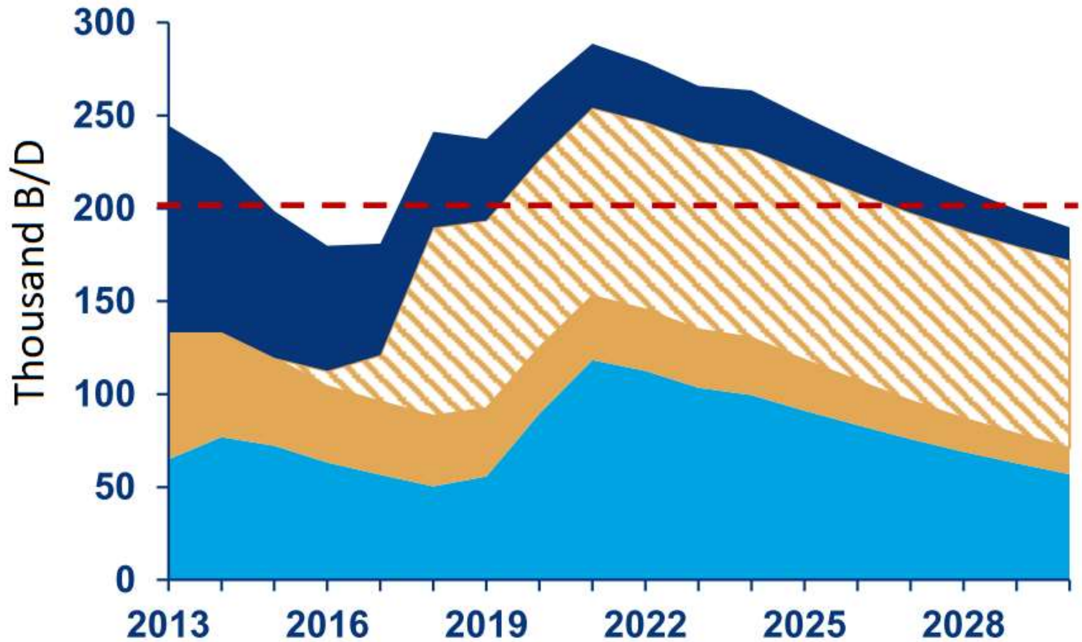


Figure D. 2 Forecasts of crude production

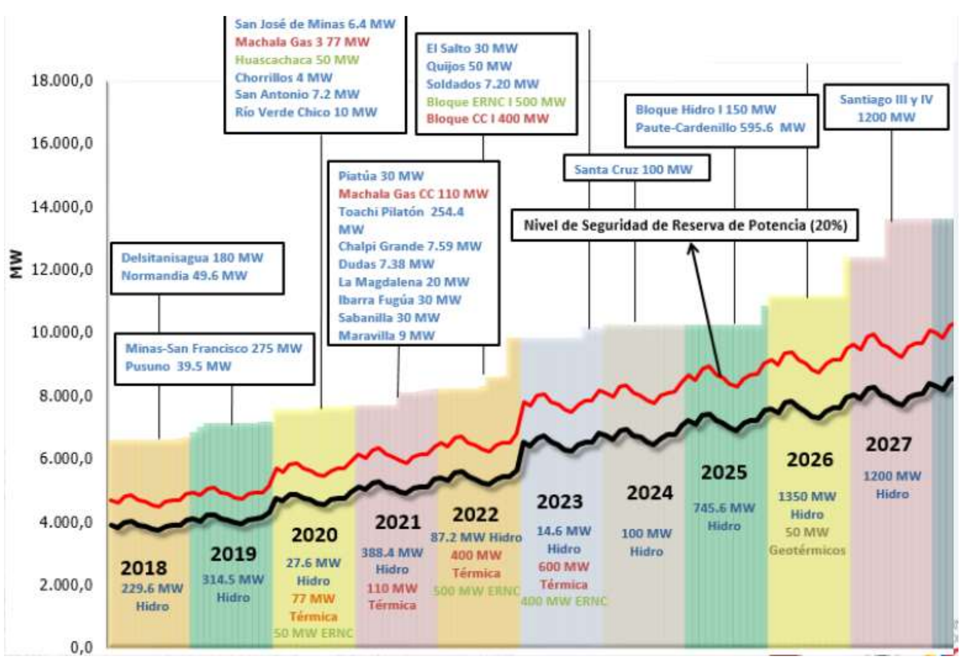


Figure D. 3 Power expansion plan