

TIMES-O&G MODEL FOR AN CONCEPTUAL O&G COMPANY

Development of a simulation model for the analysis of decarbonization scenarios applied to an integrated oil and gas supply chain in the Colombian context.

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This thesis is dedicated to:

God almighty.

My mother Carmen Cecilia.

My little dog, Emma.

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Glossary

Anthropogenic GHG: emissions associated with human activities.

Cost of the system: (also referred discounted total system cost) defines the TIMES objective function and represents the cost (capital cost, fixed and variable costs, imports cost, delivery costs, taxes, among others elements) to meet the demand and constrains of the problem.

Downstream: It consists of the activities of crude oil refining and natural gas processing, as well as the distribution of the products obtained to final consumers.

EFOM: Energy Flow and Optimization Model

Endogenous: calculation or characteristic that depends on the analysis system or it is a result of it.

Exogenous: calculation or characteristic that does not depend on the analysis system and is originated externally. It is also recognized as that which is outside the model and therefore is not inexplicable (represented) by the model.

Energy system: It is a system designed to offer energy services to end users, comprising all components related to the production, conversion, delivery, and use of energy.

Midstream: It consists of oil and gas storage, preprocessing and transportation activities.

TIMES model: an acronym for The Integrated MARKAL-EFOM System.

Upstream: It consists of hydrocarbon exploration and production activities.

Abstract

Title: Development of a simulation model for the analysis of decarbonization scenarios applied to an integrated oil and gas supply chain in the Colombian context

Autor: Julián A. Caicedo Avellaneda¹, Ariel Uribe Rodriguez², Edgar Eduardo Yañez Angarita², Ramiro Martínez Rey¹

Keywords: Energy system models, TIMES model, Oil and gas company, Colombia, decarbonization.

Description: The energy sector's mid-century energy planning has focused on meeting mitigation goals and discussing the energy transition from fossil fuels. One of the tools that have allowed us to evaluate the impact of various decarbonization strategies, such as renewable energy or hydrogen, in the energy sector are energy system models. However, the applications of these models include global, regional or national scope, while the literature review did not find any application for an organization or company in the oil and gas (O&G) sector. This work proposes to build an energy systems model, specifically a TIMES model, that allows representing the typical activities of a conceptual company dedicated to the O&G sector, so that it can be examined how this type of companies align in the energy vision of a country like Colombia, the implications for the traditional hydrocarbon business, and the role in the energy transition. The TIMES-O&G model was developed for this purpose and captures approximately 80% of Colombia's total production and 55% of the national oil company (NOC) production. Four scenarios were analyzed, which correspond to those proposed in the National Energy Plan of Colombia, exploring the integration of decarbonization technologies such as renewable energies, electricity generation from fossil fuels with and without carbon capture, hydrogen production; It also explores the implications of environmental regulations directly as the carbon rate and indirectly as the change in fossil fuel consumption that is a result of other regulations. In the evaluated scenarios, self-sufficiency in terms of oil and gas will be affected starting in 2030 by 2030 and 2040, imports of natural gas and crude oil will exceed national production, respectively; furthermore, the refineries are identified as the primary sector that must be decarbonized in the short and long term, considering their importance in the value chain they represent.

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Resumen

Título: Development of a simulation model for the analysis of decarbonization scenarios applied to an integrated oil and gas supply chain in the Colombian context

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Keywords: Energy system models, TIMES model, Oil and gas company, Colombia, decarbonization.

Descripción: La planeación energética del sector energético a mediados de siglo se ha enfocado en cumplir con las metas de mitigación y discutir la transición energética desde los combustibles fósiles. Una de las herramientas que han permitido evaluar el impacto de diversas estrategias de descarbonización, como las energías renovables o el hidrógeno, en el sector energético son los modelos de sistemas energéticos. Sin embargo, las aplicaciones de estos modelos incluyen el alcance global, regional o nacional, mientras que la revisión de la literatura no encontró ninguna aplicación para una organización o empresa del sector de petróleo y gas (O&G). Este trabajo propone construir un modelo de sistemas energéticos, específicamente un modelo TIMES, que permita representar las actividades típicas de una empresa conceptual dedicada al sector O&G, de manera que se pueda examinar cómo este tipo de empresas se alinean en la visión energética de un país como Colombia, las implicaciones para el negocio tradicional de hidrocarburos y el papel en la transición energética. El modelo TIMES-O&G fue desarrollado para este propósito y captura aproximadamente el 80% de la producción total de Colombia y el 55% de la producción de las compañías petroleras nacionales (NOC). Se analizaron cuatro escenarios, que corresponden a los planteados en el Plan Nacional de Energía de Colombia, explorando la integración de tecnologías de descarbonización como energías renovables, generación eléctrica a partir de combustibles fósiles con y sin captura de carbono, producción de hidrógeno; también se exploran las implicaciones de la regulación ambiental de manera directa como la tasa de carbono e indirectamente como el cambio en el consumo de combustibles fósiles que es resultado de otras regulaciones. En los escenarios evaluados, la autosuficiencia en materia de petróleo y gas se verá afectada a partir de 2030 para 2030 y 2040, las importaciones de gas natural y petróleo crudo superarán la producción nacional, respectivamente; además, se identifica a las refinerías como el sector primario que debe descarbonizarse en el corto y largo plazo, considerando su importancia en la cadena de valor que representan.

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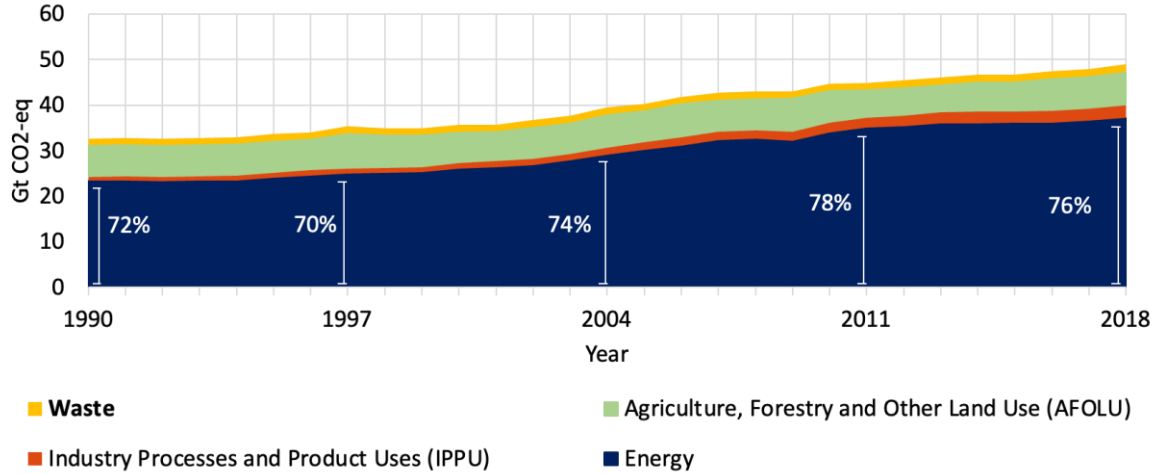
Introduction

The Intergovernmental Panel on Climate Change (IPCC) has concluded that human activities are causing global warming due to greenhouse gas (GHG) emissions, with an increase in temperature of approximately 1.0 °C compared to pre-industrial levels, and if the current trend continues, the planet's temperature will rise by at least 1.5 °C before 2050, which will imply catastrophic consequences for the environment, and therefore for humanity (IPCC, 2018).

To address climate change and its consequences, several agreements have been signed. Among them is the Paris Agreement in 2015, in which 193 parties have ratified their commitment to limit temperature increase by 1.5 °C -the ideal target is 2.0 °C- (United Nations, n.d.-b). This implies that GHG emissions be reduced by about 45% by 2030 compared to current values and achieved carbon neutrality by 2050 (United Nations, n.d.-a)

While all sectors must commit to this goal, the energy sector plays a central role. GHG emissions associated with this sector have contributed at least 72% of all global emissions from 1990-2018 (Figure 1). According to the IPCC (2006) emissions inventory methodology, the energy sector mainly comprises the exploration and exploitation of primary energy sources such as oil, natural gas, and coal; the conversion of this primary energy to secondary energy (e.g., refineries and power plants); the transmission and distribution of these fuels; and the final use of these fuels. Within the energy sector, the industry dedicated to oil and gas (O&G) should receive special monitoring since these two energy sources corresponded to 54.1% of the total primary energy supply in the world by 2019 (IEA, 2021c). Consequently, GHG emissions from this industry have a high share in the energy sector.

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Figure 1. Global anthropogenic GHG emissions 1990-2018.

Note: Own elaboration taking data from the World Resources Institute (accessed May 4, 2022). Climate Watch. The classification by sectors follows the methodology proposed by IPCC (2006).

The IEA (2021) mentions that for the energy sector to achieve carbon neutrality, an immediate and massive development of clean technologies is necessary, such as renewable energies in power generation, the use of green hydrogen, and carbon capture, utilization, and sequestration (CCUS). All this will be possible through the application of environmental policies such as carbon taxes and incentives towards renewable energies.

Achieving environmentally sustainable energy is the only one of the three pillars on which energy planning must be based according to the energy trilemma since energy security and affordability must also be considered (Plazas-Niño et al., 2022; Spittler et al., 2019; World Energy Council, 2016). Energy systems modeling (ESM) is a tool to assist in energy planning by providing an evidence base for decisions through contrasting scenarios (Giannakidis et al., 2016, 2018). ESMs represent energy systems as a whole system rather than a set of components and, in turn, allow focusing on aspects of the system that have made it possible to analyze different decarbonization scenarios in global, regional, and national

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applications (Giannakidis et al., 2018). In this order of ideas, ESMs can be a useful tool for evaluating the decarbonization of the O&G industry.

This work seeks to evaluate a technological portfolio that allows decarbonizing the activities associated with the O&G industry in 2019-2050. For this, an energy system model was built, which allows for the evaluation of different scenarios that include technological strategies that can be incorporated into the value chain of a conceptual company dedicated to the O&G sector in the short, medium, and long term.

1. Objectives

1.1 General objective

Evaluate the GHG emissions mitigation potential through a technological portfolio in a company's value chain in the O&G industry and its contribution to reducing GHG emissions.

1.2 Specific objectives

- Develop a TIMES model that represents the energy reference system of a conceptual company dedicated to the O&G sector in Colombia.
- Identify technological strategies for decarbonization and energy diversification to consolidate a technological portfolio.
- Evaluate the GHG mitigation potentials associated with the technology portfolio using the TIMES model over different time horizons up to 2050.

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- Analyze the impact on the technology portfolio due to changes in Colombian environmental policy in reference to international regulations using the TIMES model.

2. Emissions and energy planning in the oil and gas industry

2.1 Emissions in the oil and gas industry

The O&G industry value chain includes activities ranging from the production of primary energy (oil and gas extraction) to the use of final products (such as the burning of fossil fuels in consumer sectors), and GHG emissions are generated at each stage. Figure 2 presents a schematic of a reference of the energy system (RES)⁵ for the O&G industry where the main activities of the value chain are represented. GHG emissions from the O&G industry are defined by scopes (IRENA, 2021a; The Greenhouse Gas Protocol, 2015):

- **Scope 1** refers to the emissions produced during direct activities, in this case, production stages, transportation, refining, and distribution.
- **Scope 2:** The above activities require electricity, which can be self-generated - the emissions from this activity will be quantified in scope 1- or can be purchased from the national grid; in the latter case the emissions will be accounted for in scope two and it will depend on the source used to generate electricity from the national grid.

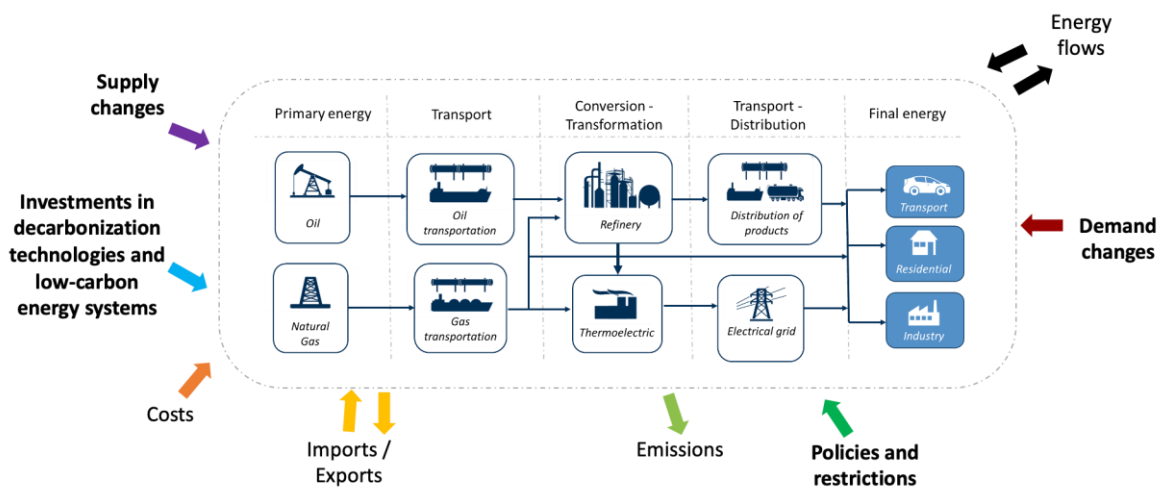
⁵ (Beller, 1976) defines the RES as a representation of all the activities required to supply various forms of energy to end-use activities, and in turn each activity can be categorized by technical-economic-environmental parameters; Likewise, the RES methodology allows the analysis of this system in the face of disturbances. In this case, the RES is designed based on the value chain of an O&G industry.

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- **Scope 3:** when the final forms of energy (e.g., gasoline and diesel) are sold and used by consumer sectors (e.g., transportation, residential, and industrial sectors), they will generate emissions that for O&G companies are quantified in scope 3.

This classification is essential because it allows companies to set specific mitigation targets for each according to the decarbonization pathways for their direct and indirect activities.

Figure 2. Simplified reference energy system of the oil and gas industry



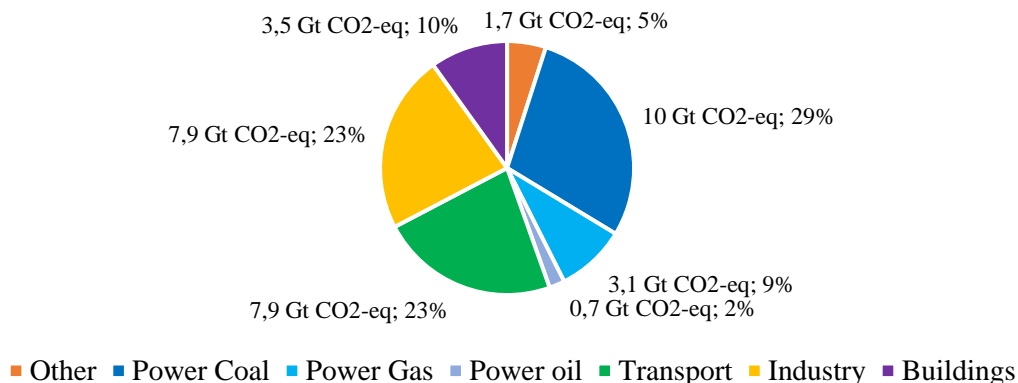
Own elaboration based on (IPCC, 2014; Loulou et al., 2016)

According to IEA (2019), in 2017, only global CO₂ emissions associated with oil and gas combustion corresponded to a 55% share of total fuel emissions -11.4 and 6.7 Gt CO₂-. On the other hand, (IEA, 2021b) estimated that, in 2021, 40% of global CH₄ emissions were associated with the operations of the O&G industry, while Beck et al. (2020) claim that the entire value chain (scope 1 + 2 + 3) accounts for 42%. The above statistics elucidate the representative impact of the O&G industry on global GHG emissions, considering that, in the last 30 years, worldwide CO₂ and CH₄ emissions had a share of 93% of total GHG -75% and 18%, respectively- (IPCC, 2022).

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The consumption of hydrocarbons is associated with the consumption sectors or by the same activities of production and transformation of primary energy. Based on the data in Figure 3, the electricity generation subsector has the highest share of GHG emissions in the energy sector with close to 40%, of which 11% come from oil and natural gas (IEA, 2020c);, according to the US EPA (2010), emissions from electricity generation and heat production represented 23% of total global emissions. On the other hand, the transport subsector represents 23% of the emissions of the energy sector (IEA, 2020c), in which oil derivatives have a participation of 91% with a drop of only 3.5% since the 70s (IEA, 2023h); besides, emissions of this subsector have been increasing from 14% to 16.2% between 2010 and 2020 respectively (Our World in Data, 2020; US EPA, 2010). Then there are the subsectors of industries and buildings, with shares of 23% and 10% of the energy sector's emissions (IEA, 2020c). In the industry, oil and natural gas use represents 37% of the energy consumed (IEA, 2023e), while in the buildings subsector, this percentage was 33% in 2022 (IEA, 2023c).

In contrast with the previous sectors, there is the categorization named others, in which primary energy production is found (including oil and natural gas) with a 5% share in the energy sector. However, other sources of information report that primary energy production activities may have a larger share: according to Our World in Data (2020), fugitive emissions from energy production represent 5.8% of total global emissions -this is 7.9% of the energy sector emissions- in 2020; the US EPA (2010), groups the activities of energy extraction, refining, processing and transportation into a category of other energy uses and estimates that their share is about 10% of total global emissions in 2010; Beck et al. (2020) quantified scope 1 and 2 emissions from O&G operations at 9% of the global emissions.

Figure 3. Global energy-related CO₂ emissions by subsector in 2018.

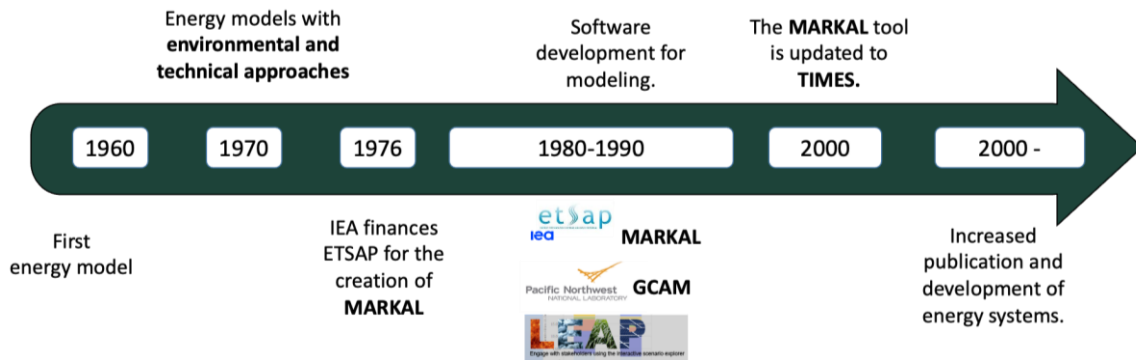
Source: (IEA, 2020c)The role of CCUS in low-carbon power systems

2.2 Energy systems models for energy planning

The history of ESMs starts around 60 years ago (see Figure 4), in which it has gone from a technical evaluation of a single commodity to technical-financial-environmental evaluations of complex energy systems and have played an essential role in policy decisions through the empirical evidence of these models (Giannakidis et al., 2016, 2018).

Different software have been developed and can be differentiated, among other aspects, by the modeling approach (Gargiulo & Gallachóir, 2013; Hall & Buckley, 2016; Plazas-Niño et al., 2022): bottom-up models that represent high engineering detail in the modeled technologies, among which are TIMES/MARKAL, MESSAGE, PET; and top-down models that focus on macroeconomic modeling such as POLES, GEMINI; hybrid models that combine the previous two approaches such as LEAP, GCAM. In addition, the models can also be divided into simulation models that predict how the trends of the analyzed system will be based on other projections or optimization models in which the modeled system is obtained at the minimum cost (Gargiulo & Gallachóir, 2013).

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Figure 4. General history of the energy system models.

Own elaboration based on Giannakidis et al. (2015)

The family of MARKAL/TIMES models is among the most recognized because these were developed and supported by the IEA - ETSAP (Energy Technology Systems Analysis Program of the International Energy Agency) since 1978 (Loulou et al., 2016). In 2010, nearly 70 countries and 250 institutions (of which 75% are active users) used this family of tools, including applications in international reports such as the IEA's World Energy Outlook and Energy Technology Perspectives (Connolly et al., 2010).

MARKAL (Market Allocation Model) was developed in the 80's, and was widely used until 2000, the year in which its successor, TIMES (The integrated MARKAL-EFOM Systems) was developed (Figure 4), which basically included and improved certain features regarding to MARKAL. Currently, ETSAP has promoted the use of TIMES for new users since 2008, while MARKAL is still available but without continuous support and updating (IEA-ETSAP, 2008).

The TIMES/MARKAL family are bottom-up, explicit, and dynamic partial equilibrium models of energy markets, written in the General Algebraic Modeling System (GAMS) language and which is open source to the public (Loulou et al., 2016). These models are based on the paradigm of linear programming optimization problems, which allow energy system modeling, energy policy analysis, monitoring of GHG mitigation objectives, and

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energy, economic, and environmental evaluation of a broad spectrum of energy systems in periods of 20, 50, or up to 100 years, under different scenarios, and at various levels such as global, multiregional, national, state and others (Gargiulo & Gallachóir, 2013; Giannakidis et al., 2015; Loulou & Labriet, 2008).

The construction of these models starts from the conceptualization of the energy reference system (Figure 2) since this represents the entire supply chain, which includes the production of primary energy. It contemplates all the processes or technologies that can be carried out to deliver energy to the end user, as can be seen in the simplified schematization in Figure 3.

It is essential to highlight that under the optimization paradigm, the system must be flexible and must contemplate different options to carry out the same process (to produce oil, there are other recovery mechanisms, categorized as primary, secondary, and tertiary recovery) because precisely the solution of the model will indicate which is the optimal option for minimizing the total cost of the system as long as demand and the restrictions that are established are met (Loulou, 2008).

2.3 State of the art of energy systems models

Table 1 summarizes the main published studies using the TIMES model to analyze the Oil & Gas industry, the diversification of energy systems, and the penetration of decarbonization technologies.

Table 1. *State of the art of TIMES model.*

Authors	Model used	Objective
(Labriet et al., 2012)	TIMES-World (TIAM-World)	Evaluates technological uncertainty and its impact under different mitigation goals. It includes integrating CSS technologies, renewable energy, energy intensity reduction, and nuclear power.

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(Gracceva & Zeniewski, 2013)	TIMES-World (TIAM-World)	It explores the uncertainty of the global potential of shale gas development and its possible impacts on the reference system, analyzing changes in the supply and distribution of demand associated with the shale gas supply chain.
(Huang et al., 2017)	TIMES-World (TIAM-World)	It studies the power generation sector and the CO ₂ -eq emission mitigation goals of technologies such as solar, wind energy, and generation from coal and gas with CSS, varying for each technology the reduction of costs over time (learning curves) through endogenous learning, multiregional learning, and multi-cluster learning.
(European Commission. Joint Research Centre. Institute for Energy & Transport., 2013)	TIMES – JCR – EU	It represents the European Union's energy reference system, which analyzes the impact of different energy policies at the level of each country or grouping of countries.
(European Commission. Joint Research Centre., 2018; Sgobbi et al., 2016)	TIMES – JCR – EU	It represents the inclusion of the hydrogen supply chain in the reference system to evaluate this technology under different scenarios. The way in which hydrogen is produced is studied according to the availability of inventory and the role in meeting the demand of specific sectors (mainly industrial and transport).
(European Commission. Joint Research Centre., 2018)	TIMES – JCR – EU	It adds technical-economic parameters and wind energy potentials to evaluate the role of this energy in the reference system of the EU and neighboring countries.
(European Commission. Joint Research Centre., 2015)	TIMES – JCR – EU	It quantifies biomass's current and future potentials for the energy sector, establishing which regions have the most significant development potential and their potential end users.
(European Commission. Joint Research Centre., 2016)	TIMES – ETM (Energy Trade Model): TIMES-TIAM, TIMES-JCR-EU	Study the potential of unconventional oil and gas development by analyzing environmental policies, changes in reserves and resources, extraction costs, international gas market, and LNG infrastructure.
(Postic, 2015; Postic et al., 2017)	TIMES – Latin American and the Caribbean	It studies the impact of each country's climate commitments on the region's energy reference system.
(De Miglio et al., 2014)	TIMES-CAC (Azerbaijan, Kazakhstan, Turkmenistan and Uzbekistan)	It explores the impact of improving domestic energy efficiency and collaboration to export fossil energy under different scenarios, including consideration of new policies that were evaluated.
(Bakdolotov et al., 2017)	TIMES-CAC	Studies the concept of export-oriented energy security, especially of oil and gas, analyzing existing export routes and possible new routes

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(Kanudia et al., 2013)	TIMES-COMET (Morocco, Portugal, Spain)	It temporally and geographically represents carbon capture and storage (CSS) to assess the scope of GHG mitigation under this technology.
(Balash et al., 2013)	MARKAL – US (EPA9rUS)	It analyzes the policies and regulations of the nine subregions of the model and how these can affect the cost of electricity, the energy basket, and the amount of emissions CO_2 .
(Yang & Ogden, 2013)	TIMES – California (US)	It analyzes the penetration of the hydrogen chain, including the development of infrastructure in 8 regions of California.
(Vaillancourt et al., 2014)	TIMES – Canada	It analyzes Canada's energy system from now until 2050 under scenarios of different crude oil prices and socioeconomic growth trends.
(Vaillancourt et al., 2017)	TIMES-Canada	It studies the energy sector's decarbonization options for fulfilling GHG mitigation goals, including a scenario using only known technologies and another scenario using disruptive technologies.
(Vaillancourt et al., 2018)	TIMES-Quebec (Canada)	It analyzes the options for new hydrocarbon exploitation projects and their implications for the distribution of energy consumption and GHG emissions associated with these projects.
(Coppens et al., 2022)	TIMES – Wallonia (Belgium)	It evaluates the possibility of meeting the 55% reduction in GHG emissions by 2030 and the actions or costs implicit in meeting this goal.
(Selosse & Ricci, 2014)	TIMES – France	It evaluates bioenergy with carbon capture and storage in France's energy system as an option to remove from the atmosphere and generate low-carbon products. CO_2
(Hugues et al., 2016)	TIMES – France	It analyzes the feasibility and impact of including the bioenergy sector in the reference system by modeling its entire supply chain.
(Krakowski et al., 2016)	TIMES – France	It analyzes the conditions that drive the penetration of renewable energies from 0 to 100% in the electricity generation system.
(Jaskólski, 2016)	MARKAL-Poland	It studies the possibilities of GHG mitigation in the power sector by diversifying the energy basket towards carbon-free energies (nuclear, biomass, wind energy) and low-carbon technologies with CSS.
(Labriet et al., 2010)	TIMES-Spain	It assesses energy strategies to meet the guidelines for renewable energy development agreed by the EU. This includes analyzing incentives for renewable energy and changing Spain's reference system when achieving GHG mitigation goals.

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(Glynn et al., 2014)	TIMES-Ireland	Studies energy vulnerability due to dependence on oil imports, low fuel diversification, and volatile prices.
(Taylor et al., 2014)	MARKAL-UK	It summarises the use, implications, and influence of studies conducted using the MARKAL-UK model over its 35-year history (for 2014).
(Simoes et al., 2015)	TIMES - Portugal	It studies the impact of exogenous assumptions such as demographic changes, economic development, technological evolution, and energy policies on GHG emissions.
(Chen et al., 2007)	MARKAL-China, MARKAL-ED-China, MARKAL-MACRO-China	It compares the results of GHG emissions with different TIMES models, which differ in how demand for energy services responds to the restrictions imposed. Evaluate mitigation policies at the technological level, changes in demand, and the impact of social welfare by carbon mitigation.
(Weilong et al., 2014)	TIMES-China	It assesses CSS's role in decarbonizing the electricity sector and analyses its resilience under different emission constraints.
(Ur Rehman et al., 2019)	TIMES-Pakistan	It studies the economic-environmental-energy nexus of the energy system by analyzing the behavior of supply, energy cost, and GHG emissions under different demand scenarios.
(Musonye et al., 2021)	TIMES-Kenya	It evaluates the technical, economic, and environmental implications of expanding the power system—including how it should be distributed—to meet three projected levels of electricity demand.
(Rečka & Ščasný, 2016)	TIMES- Czech Republic	It studies changes in the reference system and impacts on installed capacity, fuel costs, emissions under different carbon and natural gas prices scenarios, and changes in allowable emissions associated with the EU Emissions Trading System. CO_2
(Endo, 2007)	MARKAL - Japan	It studies the market for penetration of fuel cell-based vehicles and its relationship to carbon rates.
(Balyk et al., 2019)	TIMES-DK	It represents the Energy Reference System used to produce Denmark's <i>Energy and Climate Outlook</i> .
(Reedman et al., 2018)	TIMES-Australia	It evaluates different scenarios for carbon neutrality compliance across eight regions of Australia.
(Cadena & Haurie, 2001)	MARKAL-COL	It studies the implications for Colombia's economy of complying with the mitigation of GHG emissions established in the Kyoto Protocol. It also evaluates scenarios related to international cooperation considered in the Kyoto Protocol to reduce GHG emissions.
(Delgado, 2014)	MARKAL-COL	The MARKAL-COL model is used to forecast residential consumption and transportation, and from this, a financial evaluation for LNG investment in Colombia is performed.

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(Delgado et al., 2015)	MARKAL-COL, MEG4C	It uses the MARKAL-COL model to obtain energy costs in a mitigation scenario, which will affect the country's socioeconomic development. These costs are analyzed with another tool called MEG4C.
(Calderón et al., 2016)	TIAM-ECN, GCAM, MEG4C, Phoenix	Evaluate the effect of carbon rates and abatement targets on mitigation in Colombia through 4 different models caplsCO ₂ .
(Arango-Aramburo et al., 2019)	TIAM-ECN, GCAM, MEG4C, Phoenix	It evaluates the options to supply the electricity demand in the event of an impact on the hydroelectric sector (e.g., reduced water availability due to climate change), considering scenarios with environmental policies.
(Younis et al., 2021)	TIMES-CO-BBE	It complements the TIMES-CO model with technologies related to the bioenergy sector (biofuels, biochemicals, related processes in refinery, etc.), including CCS processes. Thus, the potential for integration into the energy system and reducing GHG emissions are evaluated.
(Younis et al., 2021)	TIMES-CO-BBE	It focuses on the analysis of the Colombian electrical system and its decarbonization while evaluating the challenges of the large-scale implementation of renewable energy due to its intermittency.

Each model is different because the circumstances of each country, state, or group of countries are unique. However, they agree on some characteristics: changes in demand, changes in technical-economic parameters of technologies or commodities, inclusion of new technologies or commodities, environmental policies, and trade between countries.

2.4 Research gap

National, regional, or global TIMES models can establish the relationships and synergies between the different activities, consumption sectors, and drivers of the energy sector. However, when analyzing the system as a whole, certain limitations arise regarding the O&G industry: It is usually possible to assess the share of fossil fuels in the energy sector and its categories, but it is not possible to determine the impact of changes in the energy sector on the O&G industry;⁶ since the O&G industry is one of the many sectors to be

⁶ (Browning et al., 2023) report that the results of 16 ESMs agree with the decrease in the use of natural gas and oil -which are replaced by other energy systems-, however they do not mention what impact this would have on the O&G industry or what its role would be in this transition.

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modeled, the description of the activities (e.g., production, transport, and refining) are not always detailed in-depth and are instead simplified, due to the complexity and magnitude of the system. Therefore, the traceability of emissions coming only from the O&G industry can be lost; The impact of specific decarbonization pathways (e.g. renewables or hydrogen) on the energy sector is often assessed, however there are little literature on the role of these pathways is in the specific decarbonization of O&G industry activities using ESMs.

Therefore, this work aims to build a TIMES model that allows analyzing the role of the O&G industry on the energy vision of a country and its environmental commitments. Therefore, a conceptual company dedicated to the O&G sector will be represented with greater detail in the conceptualization of its value chain. It should be noted that the literature review did not find the application of any TIMES model applied to an O&G company, so this is the first application attempt.

2.5 Proposal of the case of study

Colombia is an upper-middle-income country (World Bank Group, 2023) of 50 million inhabitants, with 77.1% of the population living in urban areas (Delgado et al., 2020a). Colombia occupies position 42 according to the classification of the trilemma index and occupies positions 32 in energy security, 74 in energy equity, and 21 in environmental sustainability (World Energy Council, 2022).

GHG emissions from Colombia were estimated at 258.8 Mt CO₂-eq for 2012 (IDEAM, 2016), and it could increase by 33% (total emissions of 345.8 Mt CO₂-eq) in 2030 if the trend continues (without implementing mitigation policies and efforts), that is, (Gobierno de Colombia, 2020).

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The energy sector participated in 30.1% of gross GHG emissions in 2012 in Colombia and 42% of net emissions (IDEAM, 2016). These emissions are closely linked to fossil fuels, from the industries dedicated to extracting primary energy (oil, gas, and coal), including the leaks involved in the process, to burning these fuels for use in other user sectors. Ends such as the transport sector. Therefore, the energy transition within the fossil fuel industry, in which the O&G industry plays an important role, can represent decreased GHG emissions.

Aligned with these goals, ECOPETROL S.A., the most essential oil company in the country, has also expressed its commitment to align its objectives with those of energy transition, climate change mitigation, and sustainability, being the first company in the O&G sector in Latin America to establish goals ambitious such as a 25% reduction in emissions in 2030 compared to 2019, while by 2050 the goal is to achieve carbon neutrality by 2050 for scopes 1 and 2, and a 50% reduction in total emissions (scope 1, 2 and 3) compared to 2019; Additionally, it is contemplated to evaluate and implement additional technologies for the substitution of fuels and the inclusion of renewable energies (ECOPETROL, 2021c).

Based on these initiatives, this study seeks to represent a conceptual company dedicated to the O&G industry in Colombia that aims to analyze the implications of GHG mitigation strategies in the value company value chain towards 2050. For this purpose, a TIMES-O&G model was built.

2.6 Thesis outline

Table 2 gives an overview of the chapters in which the specific objectives of this thesis are addressed.

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Table 2. *Structure of the thesis and specific objectives.*

Chapter	Topic	SO1	SO2	SO3	SO4
3	Modeling energy scenarios to decarbonize the oil and gas operations: Insights from the TIMES-O&G model	++			+
4	Evaluation of decarbonization options for O&G conceptual company through TIMES-O&G model		++	++	+
Appx. A	Documentation of the reference scenario	++			
Appx. B	Validation of the reference scenario	++			
Appx. C	Documentation for the disruptive scenario			+	+

Note: the symbols (+) indicate the level addressed by a specific objective (SO) chapter.

Chapter 3 presents the reference scenario of the TIMES-O model, which represents the typical activities of a conceptual company located in Colombia, keeping the value chain focused on hydrocarbons only. The fundamental core of the TIMES-O&G model built for this study is presented, including the main assumptions in each stage of the value chain. The results of this chapter allow understanding how the conceptual company would look in 2020-2050 and what implications it would have according to three supply and demand scenarios, focusing on the analysis of self-supply of hydrocarbons, activity, and emissions of the value chain. and the economic implications of each scenario. Appendix A presents all the input data and assumptions necessary to replicate the TIMES-O&G model scenarios presented in this chapter. Likewise, each company's operations' modeling detail is expanded. On the other hand, Appendix B compares the results of the baseline scenario with historical results and other projections, allowing the validation of this scenario; this appendix explains what the similarities are as well as highlights the explanation of the differences.

Chapter 4 explores the potential decarbonization of the concept company O&G and the economic implications compared to the baseline scenario set out in the previous chapter.

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First, the decarbonization pathways considered in each of the three proposed scenarios are presented and how they were modeled in the TIMES-O&G model. In the same way, different projections of environmental policies (carbon rate) are included. Then, by contrasting scenarios, the most promising technologies to decarbonize the company are evaluated, and the impact environmental policies may have on the decarbonization of the company is established. Appendix C presents the data and assumptions for decarbonization technologies, as well as the environmental policies introduced in this chapter.

3. Assessment of the Colombian long-term energy planning scenarios for the national hydrocarbon value chain: Insights from the TIMES-O&G model

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Abstract

Using energy system modeling tools has successfully contributed to energy planning for mid-century energy sector decarbonization goals at different levels, such as national, regional, and global scenarios. These tools provide scientific evidence to define long-term strategies per the objectives set, such as energy self-sufficiency, energy transition, and decarbonization, which includes each sector's actions. Hydrocarbons are one of the most studied sectors due to their relevance in the energy sector. However, more work needs to be done to analyze the implications of these actions and explore the role of this sector in the strategy of the country or region. This study models a conceptual company's oil and gas value chain at a country level, exploring its role in the long-term vision of Colombian energy strategy. We developed a TIMES-O&G model and tested it on three scenarios based on Colombia's National Energy Plan. In the short and medium term, the possibility of adding new resources could indicate how quickly the Colombian hydrocarbon market will lose its self-sufficiency since by 2030 and 2040, imports of natural gas and crude oil will exceed national production, respectively, leading O&G company in Colombia would lose its role as a producer of hydrocarbons, and from 2040, its value chain would be limited to being an importer of raw materials for refining to meet the national fuel demand; the preceding would imply an increase in costs of 15 and 18% of the system for the upgrading and inflection scenarios concerning the base case scenario. Moreover, the refineries are identified as the primary sector that must be decarbonized in the short and long term, considering their importance in the value chain they represent.

Keywords: energy systems modeling; TIMES models; Colombia; oil and gas industry.

3.1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) has concluded that human activities are causing global warming through the emission of greenhouse gases (GHG), which will lead to catastrophic consequences for the environment and humanity (IPCC, 2018). To combat climate change and its implications, different agreements have been signed, such as the Paris Agreement in 2015, of which 193 parties have ratified their commitment to limit the temperature increase to 1.5 °C (United Nations, n.d.-b); this would be possible if emissions were reduced by 2030 and carbon neutrality was achieved by 2050 (United Nations, n.d.-a). The energy sector plays a vital role in this commitment, as GHG emissions associated with their industrial activities have contributed at least 72% of all global emissions from 1990-2018 (World Energy Resources, n.d.). The oil and gas (O&G) industry should receive special attention within the energy sector, as in 2019, these two fuels accounted for 54.1% of the world's total primary energy supply (IEA, n.d.).

The development of energy system models (ESMs) began in the 1960s. Still, it was not until the first oil crisis in 1973 that the importance of these analytics tools for long-term strategic energy planning was highlighted (Giannakidis et al., 2015; Helm, 2002; Pfenninger et al., 2014). Since then, several ESMs such as MESSAGE, GCAM, EnergyPlan, and LEAP have been developed and applied according to their numerical approach, demand-supply perspective, technological detail, and analysis objective (Beeck, 1999; Hall & Buckley, 2016; Kang et al., 2020; Kueppers et al., 2021; Plazas-Niño et al., 2022; Rahimi Mougouei & Mortazavi, 2017). EMS applications seek to analyze the long-term economic, environmental, and technical implications of the energy system for the scale of each study, which are usually at a global, regional, national, and local (Groppi et al., 2023; IEA-ETSAP, 2022; H. Zhang et al., 2022; Zhou et al., 2024). EMSs can focus on evaluating the energy system globally or

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concentrate on some industries (aluminum, steel) or commodities (i.e., renewable energy, water, emissions) (Afsari Mamaghani et al., 2023; Deng et al., 2022; Johnson et al., 2023). Some applications focus on the hydrocarbon industry due to its relevance in the future energy pathways (Chiodi et al., 2016; European Commission. Joint Research Centre., 2016; Gracceva & Zeniewski, 2013; McGlade et al., 2018), energy security (Durand-Lasserve et al., 2023; Espinoza et al., 2022; Glynn et al., 2014), and decarbonization (Colbertaldo et al., 2023; Kouchaki-Penchah et al., 2022; McGlade & Ekins, 2014; Vaillancourt et al., 2018). However, in these cases, the O&G industry is one of the many elements of the system; hence, the discussions have not been carried out from the point of view of O&G companies and the implications on the energy transition.

Petroleum and gas companies have started to analyze energy transition and GHG mitigation strategies. According to the International Renewable Energy Agency - (IRENA), five major O&G companies have defined goals to reduce their emissions (Asmelash & Gorini, 2021). In this context, ESM can play an essential role in energy planning because it allows exploring energy flows, costs, and emissions throughout the entire hydrocarbon value chain, as well as exploring scenarios that ensure energy security and compliance with the environmental goals of both the companies and the country in which they operate.

The Colombian hydrocarbon industry contributed 2.1% of the national gross domestic product (GDP) in 2021, representing 12% of the nation's current income, accounting for 32% of exports, especially crude oil (MINENERGIA et al., 2021). Nonetheless, in the future, energy security might be affected by the reserves/production ratio (R/P) for petroleum and gas, which at the end of 2020 were estimated at 7.7 and 6.3 years, respectively (ANH, 2021a). Consequently, the national energy plan developed by the UPME (Energy Mining Planning Unit) proposed a scenario where Colombia would demand more natural gas than its domestic

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production, becoming a gas importer in the South American region. (BP, 2021)(ANH, 2021a)(UPME, 2020a) Moreover, Colombia, as a country member of the Paris Agreement, has expressed its nationally determined contributions (NDCs), establishing goals such as reducing GHG emissions by 51% by 2030 -concerning the baseline projections- and achieving carbon neutrality in 2050 (Gobierno de Colombia, 2020). To the best of our knowledge, several ESMs have been proposed to assess the Colombian energy system (Arango-Aramburo et al., 2019; Bataille et al., 2020; Calderón et al., 2016; Correa-Laguna et al., 2021; Delgado et al., 2015, 2020; Nieves et al., 2019; Younis et al., 2021, 2022), but none has focused on the study of the hydrocarbon sector and the interaction of these industrial activities to keep Colombia's energy security and simultaneously to meet the NDCs.

This study seeks to contribute to the discussion on the implications for an O&G company of aligning itself with the energy trends of the country in which it is operating through the study of the petroleum and gas value chain of a company located in Colombia, which is modeled using an ESM methodology. Our model is called TIMES-O&G, which considers the extraction of energy resources, their transportation and transformation at the refineries, and the balance between imports and exports of commodities such as petroleum, gas, and medium distillates. Since TIMES-O&G focuses on the hydrocarbon industry, our model can analyze the interactions of this sector within the national energy plan, aiming to adapt it to the energy scenarios proposed by the Colombian government and also to offer other scenarios that might not be evident, such as decarbonization and energy transition, considering the aggregation of the petroleum and gas operations into a national ESM.

The novelties of this study are mainly focused on the difference between TIMES-O&G and most of the TIMES models presented previously in the literature (see section 2.3

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State of the art of energy systems models) present a state of the art of the applications of the TIMES models, which are mentioned as follows:

- Usually, TIMES models simplify the hydrocarbon value chain (a single process for hydrocarbon production and a single process for refinery). However, the TIMES-O&G model details these activities in greater depth through extensive documentation (several processes to represent production and refinery) based on actual data from a vertical-integrated oil and gas company.
- While specific applications in TIMES models have begun to increase the spatial resolution of particular sectors (especially renewable energy), TIMES-O&G is the first application that includes an improvement in the spatial resolution of the hydrocarbon value chain by differentiates the two primary refineries in the country and by defining the basins sedimentary (which group together different oilfields). It allows that each basin has its technical-economic parameters for hydrocarbon production activities, electricity generation from fossil and renewable sources, among others.
- TIMES models do not usually consider the energy consumption in oil production and refining (electricity or fuel as an input). However, the TIMES-O&G model detailed these activities through subprocesses.
- Based on the previous approach, the TIMES-O&G model allows quantifying emissions of scope 3 (as is done by global and regional TIMES models) and scopes 1 and 2 of the O&G industry.
- TIMES are usually limited to global, national, regional, and local scopes, but the TIMES-O&G is the first model published with a scope application of a vertically

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integrated oil and gas company. At the same time, we validate the results of this company's application to the national application to discuss the main differences between these approaches.

The above can be extended to other TIMES models since we present the energy reference system with the newly defined subprocesses and supplementary material (Appendix A) detailing the type and possible data sources necessary to determine the subprocesses. For this, it is not required to change the code in GAMS of the TIMES model since the currently defined characteristics are used.

This paper is organized as follows: section 2 provides details on the TIMES-O&G model that was developed to carry out this research, including the optimization problem as well as the assumptions and sources of information for the characterization of the processes included in the model; then, in section 3, the analysis of the results obtained through the TIMES-O&G model will be presented, including the representation of O&G activities, the role of the O&G company in the country's supply, the cost of the system and the GHG emissions associated with the O&G value chain.

3.2. Methods and data

3.2.1 Modeling framework

To evaluate long-term decarbonization scenarios, we use the TIMES models since these have been successfully used in global, national, and regional applications, and unlike other models, such as top-down models, they allow the representation of a system with great detail of technologies to optimize the cost of the system. The TIMES models (an acronym for The Integrated MARKAL-EFOM System) are bottom-up, explicit, open source, and dynamic partial equilibrium models written in GAMS (Loulou, Lehtilä, et al., 2021), which

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allow energy system modeling, energy policy analysis, monitoring of GHG mitigation objectives, and the technical, economic and environmental evaluation of a broad spectrum of energy systems in periods of 20, 50, or up to 100 years (Gargiulo & Gallachóir, 2013; Giannakidis et al., 2016; Loulou et al., 2016). These models are cast as linear programming (LP) optimization problems. Still, some options -such as lumpy investment extension and endogenous technological learning- can turn the formulation into a mixed integer programming (MIP) problem (Loulou, Wright et al., 2021). TIMES models are complex optimization problems (in this case, with more than 14,000 equations). The TIMES models are coded in GAMS; due to the large volume of input data, the TIMES-O&G model management uses the VEDA2.0 data handling system, which converts data and assumptions into the TIMES code. The modeler does not need extensive knowledge of the TIMES code in GAMS to build a TIMES model (Goldstein et al., 2020). However, a conceptual simplification of the objective function, decision variables, and constraints of the problem is presented below. To better understand the TIMES model, refer to the official documentation (Loulou, 2008a; Loulou, Lehtilä, et al., 2021).

The objective function is to minimize the net present value (NPV) of the entire system in the time horizon of the analysis to meet the demand. The formulation of the NPV can be simplified as the linear combination shown in equation 1 (Giannakidis et al., 2018; Loulou et al., 2016; Younis et al., 2021), which includes capital investment respectively, CAPEX (CC), and the total installed capacity (IC); fixed operational costs (FC) according to the IC; variable operational costs (VC) according to the production of a commodity (E_{out}); and trade market according to the imports and exports of commodities (E_{imp} and E_{exp} respectively)

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and prices stipulated (P). This calculation is made for all periods (and for each process and flow of commodities represented with the t , p , and c indexes, respectively).

$$\begin{aligned}
 Min = \sum_t \left(\sum_p CRF \times CC \times IC + \sum_p FC \times IC \right. \\
 \left. + \sum_{p,c} VC \times E_{out} \sum_c (P_{imp} - E_{imp}) \times (P_{exp} \times E_{exp}) \right) \quad (1)
 \end{aligned}$$

While minimizing the NPV, the model will exogenously calculate the decision variables discussed below. To supply end-user energy services or commodity demand, the model will define the additions to the existing capacities of each technology in the period and region that are necessary; for example, for a future period, the demand for LPG will increase, exceeding the supply capacity, so that, it will be required to invest in new technologies that allow producing LPG (i.e., refineries or natural gas processing plants). Based on the above variable, the installed capacity of each technology in a specific region and period is also calculated, which is defined by the residual capacity at the beginning of the time horizon and the new installed capacity at the period under consideration, provided that its useful life has not yet ended, for example, the capacity of the LPG processing technology is computed based on the existing facilities that have not exhausted their useful life and the new investments in each period of the analysis horizon. In addition, each time the level of activity of each technology is determined, i.e., how much of its installed capacity is used, for example, for a certain specific period, it could happen that, even with an installed capacity, the technology is not carried out (i.e. it could happen if there is no demand for the technology's output commodities, or if this demand is supplied at a lower cost by another technology); in the

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same way, based on the activity, the input and output flows of commodities in each process are defined. Another decision variable is the definition of commodity trade so that an excess or a requirement - which is not technically or economically feasible through an existing or new process - of a commodity in a particular region is exported (sold to the other areas) or imported (bought from other regions) respectively, according to the prices defined in the model exogenously or endogenously. Finally, different variables are not strictly necessary but are convenient for reporting or placing restrictions on these variables, such as the total amount of commodities consumed or produced; for example, the model will calculate the production of all refinery distillates, and it is possible to group them all in one group to apply some restriction or limit.

The calculation of the above decision variables is subject to constraints discussed below. The activity of technology is limited at most to its installed capacity at that period and its availability factor; the latter is significant in defining the capacity or plant factor of renewable energies, but it is also applied to other technologies. Regarding commodities, there must be a balance for each period and region that is defined by the type of commodity; for example, for commodities that are demanded, production plus import of a commodity must be equal to consumption and export; however, for other commodities (i.e., emissions), the above equation must be represented by an inequality, to allow for a positive or negative balance. In addition, for each technology, the dependence between the variable output and input flow must be defined to avoid indeterminacy; in most cases, this is done through a constant that represents the efficiency of the process; for example, a refining process may establish that for each barrel of crude oil that enters, only a percentage of it will be used to produce fossil fuels. On the other hand, specific processes are flexible to the extent that the inputs or outputs of a process contain different elements, so it is necessary to establish rules

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to limit the flexibility of the process; for example, the outputs of a refinery can be various components (i.e., gasoline, diesel, fuel oil, among others), and it is possible to establish rules on the outputs (i.e., half of the output products will be diesel and gasoline). There may also be restrictions associated with commodities so that the quantities produced, consumed, imported, and exported can be limited; this can be used to set limits on emissions globally or by sector, as well as to define hydrocarbon reserves. Finally, the latest restrictions can be imposed for individual commodities or processes and grouping these.

3.2.2 Model structure

TIMES-O&G can represent the petroleum and gas value chain but can be extended to any energy system value chain; it was applied to a case study considering the hydrocarbon sector in Colombia.

The primary operations of the hydrocarbon industry are modeled as follows: the production and conversion of hydrocarbons are analyzed spatially by distinguishing between sedimentary basins and the location of the two large refineries that operate in Colombia, as well as distinguishing between the availability of solar and wind energy in these regions; priority is given to energy sources that are related -or may be connected in decarbonization scenarios- to the O&G value chain; there are no details on the demand technologies as it is outside the scope of the company's operations.

Even so, the TIMES-O&G model was inspired by the generalities of the TIMES-CO-BBE model -which in turn is an improvement of the TIMES-CO-9 model- such as both are based on the same geographical context (Colombia) and share the same analysis period (until 2050); representation of demand for energy and energy services by sectors; analysis scenarios

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based on mitigation goals, among others. More details about the differences and similarities between the TIMES-O&G and other TIMES models are presented in Appendix A, section 1.

The TIMES-O&G model covers the time horizon between 2019 and 2050. The resolution of time slices remains at an annual level considering the following assumptions: the activity of the process related to the O&G is usually reported monthly. However, there are no significant variations from month to month -e.g., the coefficient of variation for oil and gas production and refinery loading in 2019 is 1, 4, and 6%, respectively (ANH, 2021b; UPME, 2021)-. Since the activity of the processes is annual, the energy/electricity requirement for these will also be annual. Therefore, the self-generation processes -including those from renewable sources such as solar and wind energy- were modeled by averaging their technical parameters. The TIMES-O&G model was contrasted with projections from other studies and available historical data, and its respective analysis is presented in Appendix B.

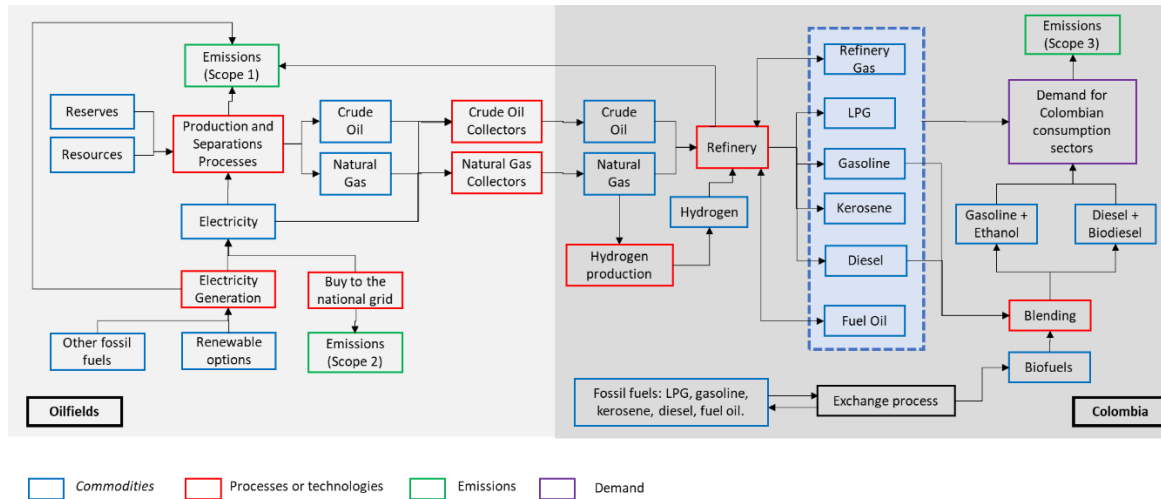
The TIMES-O&G model topology is given by the reference energy system (RES) shown in Figure 5. TIMES-O&G comprises three modules: supply (resources exploitation, production, and transportation), conversion processes (mainly crude oil refining and electricity generation), and demand side (petroleum-based fuel consumption). Moreover, fuel import and export are also allowed, and environmental policies are considered. Only commodities related to the hydrocarbon value chain were considered in the RES (see Appendix A, section 2.2). In addition, electricity generation was modeled to fill the energy demand for the O&G operations.

The emissions produced during direct activities (scope 1) at the production, transportation, and refining echelons are estimated by TIMES-O&G. Moreover, scope two emissions are computed by electricity purchases from the national grid. The emissions

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associated with petroleum-based fuel are considered scope 3; either it is consumed at the Colombian market or exported. See Appendix A, section 2.5. In the next section, we describe each TIMES-O&G component.

Figure 5. Simplified reference energy system (RES) of TIMES-O&G.



3.2.2.1 Supply side

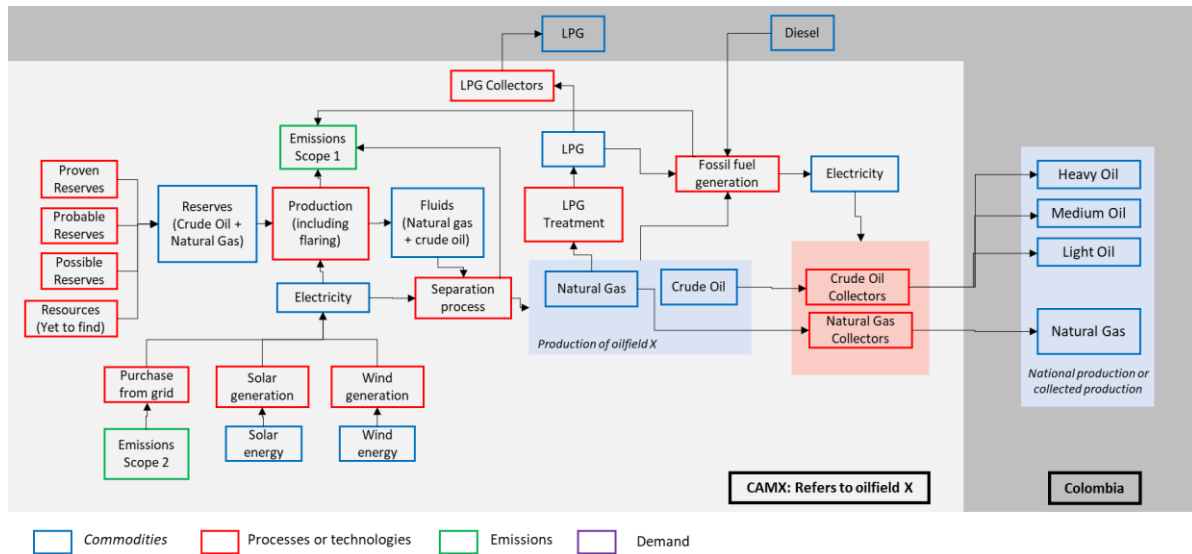
The TIMES-O&G model represents the hydrocarbon production from 35 oilfields, which are aggregated into six sedimentary basins: Guajira (GU) -offshore basin-, Eastern Plains (LLO), Lower Magdalena Valley (VIM), Upper Magdalena Valley (VSM), Middle Magdalena Valley (VMM), and Putumayo (PU). More details on the selection of oilfields and their generalities can be found in Appendix A, sections 3.2- 3.4. These oilfields are characterized by three attributes: The type of fluid produced, natural gas, and crude oil. The latter can be classified as light, medium, or heavy according to its API gravity, the production declination curve, and the estimated reserves (Global Data, n.d.; Offshore Technology, n.d.), (ANH, 2021b). Moreover, we added another sedimentary basin to consider the resources yet to be found (YTF); see Appendix A, section 3.4-3.7.

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The RES for the supply side modeled in TIMES-O&G is shown in Figure 6. Each sedimentary basin was modeled according to its particularities and available data; for details of the techno-economic and environmental parameters used in each sedimentary basin, see Appendix A, section 3.1-3.7. The RES indicates that the reserves of hydrocarbons are produced by the flaring of natural gas, which accounts for scope one emissions; then, the mix of natural gas and crude oil is separated and routed to the natural gas and crude collectors. Note that the gas-oil ratio manages the separation process, which is known for each oilfield. These operations demand electricity, which can be purchased from the national grid or self-generated by renewable energy and burning fossil fuel (03.2.2.2 Conversion processes).

The output of the supply side module is the natural gas and crude oil availability for further transformation at the refineries or to fulfill domestic needs for the Colombian industry and in case of surplus to export. Note that TIMES-O&G and, in general, no ESM models can represent the transportation activities explicitly. Instead, we assume that the crude oil and natural gas at the collectors consider the transportation cost, capacity, and emissions. This assumption might be valid since transport processes do not account for more than 4% of energy consumption and emissions concerning the entire value chain (see Appendix A, section 2.1) (E. Yáñez et al., 2018). Another critical assumption in our model is that we do not consider the distribution of the refined product; thus, all the products are sold at the refinery gate.

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Figure 6. RES of the TIMES-O&G supply side**3.2.2.2 Conversion processes**

The conversion module comprises the technologies for power generation and the transformation of natural gas and petroleum into fossil fuels that the Colombian industry and transportation sector demands.

A mix of crude oil (light, medium, and heavy) is fed to the refinery to produce refinery gas, LPG, jet, gasoline, diesel, and fuel oil; the yields of these refined products depend on the crude oil quality and the refinery configuration. The refinery can import and blend these refined products to meet quality specifications for the gasoline and diesel (e.g., Sulphur content, octane number, and cetane index). Moreover, combining up to 10% volume gasoline-ethanol and diesel-biodiesel can improve the quality of these products (MINMINAS, 2019; Resolución 40730 de 2019, 2019). The fulfillment of the domestic demand for fossil fuel is the main target of the refinery, and in the case of fuel surpluses, it is exported. TIMES O&G represents the two primary refineries in Colombia (ECOPETROL, 2019). These refineries were modeled according to Figure 7, considering their processing capacity, feedstock, fuel consumption in the process (natural gas, fuel oil, refinery gas,

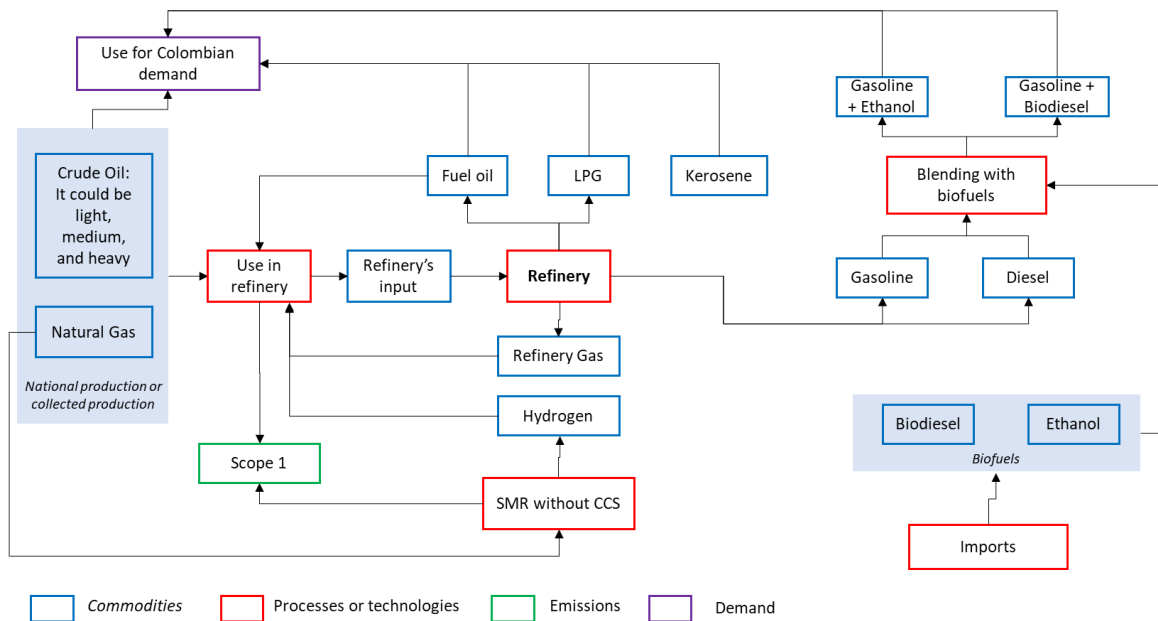
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hydrogen), and fuel production. We assume that the refineries provide the utilities they need (low- and high-pressure steam, self-generation, and electricity purchases) as they have been operating in recent years. We use the technical-economic parameters to model the refineries (REFICAR, 2020; UPME, 2019a, 2019b; E. Yáñez et al., 2018; É. Yáñez et al., 2021). See Appendix A, section 4.

Natural gas is sent to pretreatment units, where LPG is obtained for further use in power generation at the oilfield, while clean gas is routed to the gas collectors (Appendix A, section 3.8). In addition to LPG, we consider that the energy matrix for self-generation is composed of diesel and crude oil. In case of a deficit in electricity generation capacity, it is supplied from the national grid purchases.

The capacity for each sedimentary basin was aggregated according to the UPME database (UPME, 2014) and characterized by its efficiency, utilization factor, and OPEX (both fixed and variable). Since new capacities could be added for the resources to be developed (YTF) and the model's time horizon is greater than the useful life of technologies, we consider thermal and renewable generation technologies, with three levels of development every ten years starting in 2020. The technical and economic data of existing and non-existing technologies were taken mainly from the NREL Annual Technology Baseline and PRIMES model-18 database (Capros & Evangelopoulou, 2018; Farnossh, 2021; NREL, n.d., 2021); more detail on these parameters can be found in Appendix A, section 3.9.

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Figure 7. RES of the TIMES-O&G conversion module**3.2.2.3 Demand side**

This study is based on the assumptions made by the PEN (*Plan Energético Nacional*), which projects the demand for commodities in the period 2019-2050 under four scenarios (UPME, 2020c, 2020b) (see Appendix A, section 2.3). For each scenario, five consumption sectors are defined -agriculture, construction, and mining; tertiary; residential; industrial; and transportation-and for each of these, the demand for commodities - hydrogen, charcoal, coke, avgas, waste, crude oil, fuel oil, LPG, firewood, bagasse, mineral coal, kerosene-jet, gas natural, electricity, gasoline, diesel- is presented. However, only commodities provided by the O&G industry were considered (see Appendix A, sections 2.2 and 2.3). Thus, we only consider the demand for fossil fuels at the lowest possible cost.

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3.2.2.4 Commercial exchange

When the national demand for fossil fuel is satisfied by the O&G sector, and there is a surplus in fossil fuel production, it can be exported. Otherwise, natural gas, diesel, and gasoline must be imported mainly. It is assumed that fossil fuel can be traded according to the price projections of the Annual Energy Outlook 2020 developed by the EIA (U.S. EIA, 2019) using the reference scenario (see Appendix A, section 2.4).

3.2.2.5 Environmental policies

Colombia has regulated the carbon tax through Article 222 of Law 1819 of 2019, which establishes a price for the emission of GHG through the combustion of fossil fuels (Ley 1819 de 2016, 2016). This figure was 4.96 USD/t CO₂-eq in 2022 (IETA, 2022). However, for this study, a tax of 7 USD/t CO₂-eq (0.007 MUSD/kt CO₂-eq) will be assumed to be aligned with related ECOPETROL studies (E. Yáñez et al., 2018). This carbon tax does not apply to biofuels, natural gas used in domestic consumption sectors, or fuels exported by current regulation (see Appendix A, section 4.5).

3.2.2.6 Scenario analysis

Since the demand of the TIMES-O&G model was stipulated exogenously from the PEN (UPME, 2020c, 2020b), the scenarios that will be used in this study (see Table 3) were built in line with the assumptions of the PEN scenarios, which can be summarized as follows: the updating scenario (S1) is aligned with current trends; the upgrading scenario (S2) focus on the massification of natural gas as a step towards the decarbonization; and the inflection scenario (S3) focuses on the beginning of the electrification economy (see Appendix A, section 2.3). Thus, S1 is the reference scenario considered in the TIMES-O&G model (see Appendix B).

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Table 3. Description of the scenarios considered by the TIMES-O&G model.

Module	Scenario variables	S1	S2	S3
	Scenario of consumption*	Updating	Upgrading	Inflection
Demand side	Final consumption in the energy sector in 2050, PJ	1,905	1,685	1,668
	Final consumption of fossil fuels in 2050, PJ**	1,291 (68%)	1,146 (68%)	1,013 (61%)
	Total Emissions in 2050, Mt CO ₂ -eq***	90	76	69
	Hydrocarbon reserves scenario	Medium (16,467 PJ)	Low (14,778 PJ)	
Supply-side	YTF hydrocarbon resources scenario	Medium (8,767 PJ)	Low (429 PJ)	
	New thermal plants	Yes (GAS-CT, GAS-CC, GAS-CC-CCS, diesel, and fuel oil generators)		
Conversion processes	New renewable capacities	Yes (Solar-PV and Land-Based Wind Energy)		
	Blending with biofuels	10%	15%	
	LPG Scenario****	Medium (11.51 PJ)	High (21.88 PJ)	
	Changes in refinery outputs	Yes		
fuel price	Crude oil prices in 2050	16,9 MUSD2019/PJ		

*Refers to the selected PEN scenario. There is another scenario called "disruptive," but it was not considered in this study because it includes the penetration of hydrogen and technologies associated with its value chain, which is outside the scope of this study.

**It refers to the final consumption of fossil fuels related to the O&G sector, which is the demand of the TIMES-O&G model.

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***It refers to the total emissions from consumption by final users of the energy sector in Colombia, as estimated by the PEN.

**** Regarding LPG processing capacities in oilfields, see Annex 2, section 3.8.

****The prices of crude oil, natural gas, and hydrocarbon derivatives were taken from the International Energy Agency AEO-2020 reference scenario; see Annexe 1, section 2.4.

3.3 Main results

3.3.1 Validation of the model

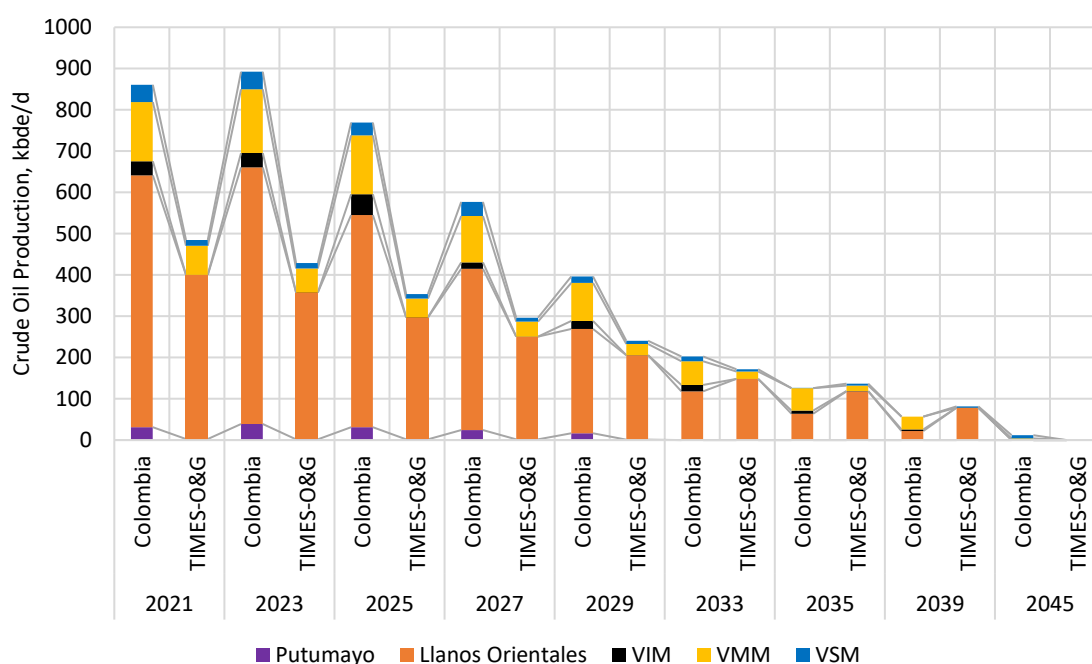
There is no predictive model of this type developed for this company or a similar one (notice that the TIMES-CO models are designed in the national context while TIMES-O&G focuses only on an O&G company located in Colombia), which is why a direct comparison of this model cannot be made. However, the TIMES-O&G model can be validated through its comparison with historical data and other predictions made for the Colombian (more details in Appendix B, which explores the validation process of the model and tests it against other predictive models and historical data). Here are some of the most relevant comparisons.

The TIMES-O&G model effectively represents at least 80% and 55% of the production of Colombia and ECOPETROL (largest producer in the country), respectively, not only for the 2019 -year base- but also for 2020 and 2021. Figure 8 compares the declared production for Colombia and the estimated output for the TIMES-O&G model by sedimentary basins, and both forecast that the Eastern Plains basin continues to be the one with the highest participation both for Colombia and for the TIMES-O&G model, followed by the VMM and VSM basin. This trend is valid for the base year and the period presented (Appendix B, sections 3.1.1 and 3.2). Besides, oil production for 2045 is estimated to be approximately zero in the two projections. The differences in the magnitude of hydrocarbon production are due to the nature of the TIMES-O&G model, which represents one of the many companies that operate in Colombia; at the same time, differences in the production of

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some sedimentary basins are explained by considering that there are regions in which some companies do not have high participation in the production of hydrocarbons, (i.e. in the base year, the ECOPETROL production in the department of Putumayo presented only 26% of the total reported for this region (ANH, 2021b)). As well as in the supply of crude oil, the TIMES-O&G model satisfactorily reproduces the natural gas supply (see more details in Appendix B, sections 3.1.2 and 3.3).

Figure 8. Crude oil supply by sedimentary basins



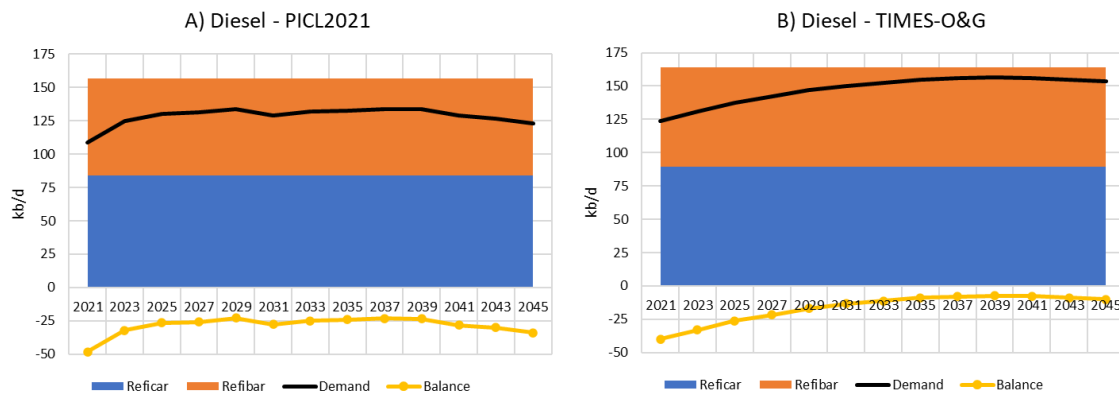
Note: Data for Colombia were taken from the declared production reported in the 2021 liquid fuel supply plan UPME—figure 4-2 [67]. In the same way that UPME does not consider discoveries (yet to find resources), neither do the results presented to TIMES-O&G, which are the results of scenario S1.

In the case of the refineries, the comparison between Colombia and the O&G company represented by the TIMES model is direct since the company considers the two refineries that supply the national market. The amount of crude loaded into the refineries and the composition of the light product refinery outputs are similar between the models, and the

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historical data for 2019-2021 are identical: the main differences are observed for the year 2020 due to the behavior demand caused due to the pandemic when the difference in crude oil input between the models is around 18% and with a variation of 4% in the output composition, while in the other two years (2019 and 2021) the differences are less than 4% both in the refinery load and output composition (more details are found in Appendix B, section 3.4-3.5). The TIMES-O&G model effectively represents the fuel balance at the national level; in the case of diesel, the national production manages to supply the national demand during the entire period of analysis and even allows the export of this fuel estimated on average of 18% and 10% according to the UPME report and the TIMES-O&G model respectively (Figure 9); the difference in export value are explained because the demand of each projection is different, which is 156 kb/d according to the TIMES-O&G model, 16.8% higher than the maximum demand in the UPME report -stipulated at 134 kb/d-.

Figure 9. Comparison of long-term projections for the diesel balance



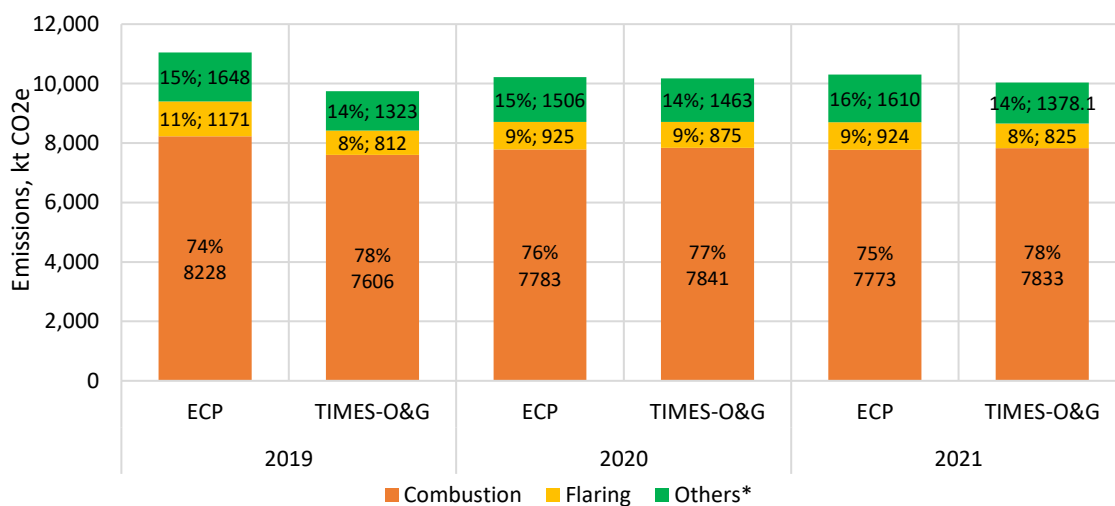
Note: The data in graph A were taken from the UPME 2021 indicative liquid fuel supply plan, graphs 4-15 [67]. The balance represents demand minus supply; a positive value represents an import, and a negative value represents an export.

The TIMES-O&G model accounts for the following sources (more detail in Appendix A, section 2.5): emissions that imply the combustion of fuels for different uses; the flaring of

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natural gas in production; other emissions established by activity emission factors -taken from a study that analyzed hydrocarbon's value chain in Colombia(E. Yáñez et al., 2018)- and therefore the source is not precisely established. TIMES-O&G model allows replicating that the primary source of emissions is combustion, representing between 77% and 78% of total emissions, a range similar to that established by the reference's company of 74% and 77% (Figure 10). Regarding emissions from flaring, they continue to represent 8-9% and between 9-11% of total emissions according to the TIMES-O&G model and reference company, respectively.

Figure 10. Emissions per source in scope 1 + scope 2.



Note: Emissions data were taken from the company's 2018-2021 GHG inventory [68]. In the case of ECP, others refer to the sum of fugitives, mobiles, and vents.

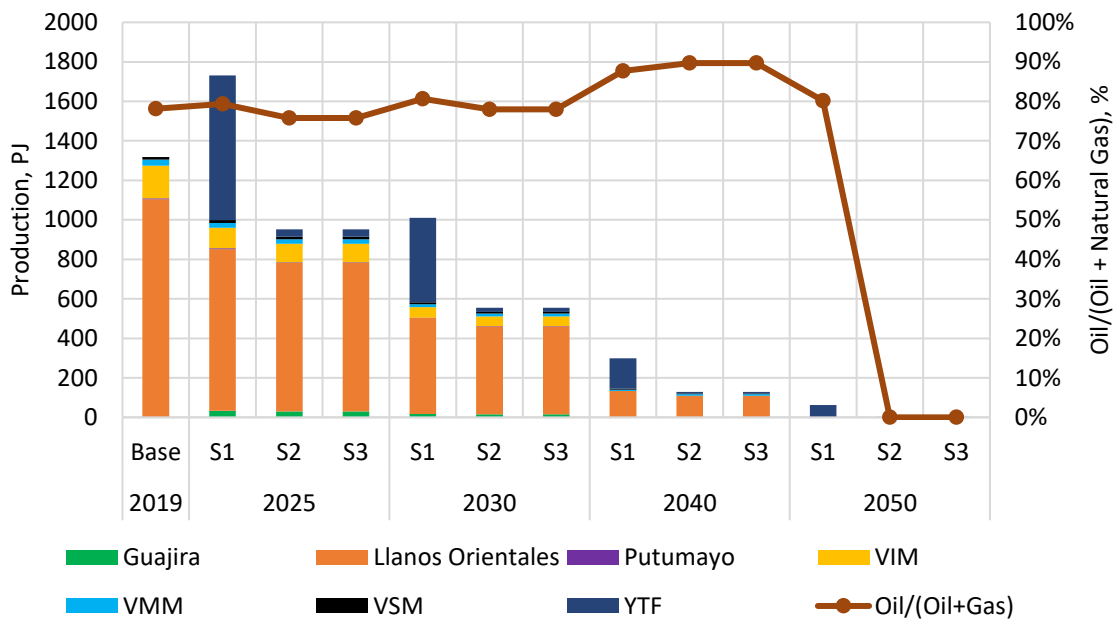
3.3.2 Supply of hydrocarbons

Like the reference company, the hydrocarbon production of the modeled O&G company is mainly concentrated in crude oil (around 80% and 90% of the equivalent total output in the time horizon). Scenario S1 considers the YTF resources to represent 42% of the

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total production by 2025, with crude oil to natural gas production ratio, $COTNGPR = \frac{Oil}{Oil+NaturalGas} = 0.8$. In this scenario, the proportion of YTF on hydrocarbon production will increase to 50% by 2040 and reach 100% of the crude oil supply by 2050. On the contrary, crude oil production at the six sedimentary basins will plummet to zero, but the COTNGPR will remain steady at 0.80 by 2050. Production decrease is more accelerated in scenarios S2 and S3 since they consider a low incorporation of reserves and YTF.

Figure 11. Production of hydrocarbons in the TIMES-O&G model.



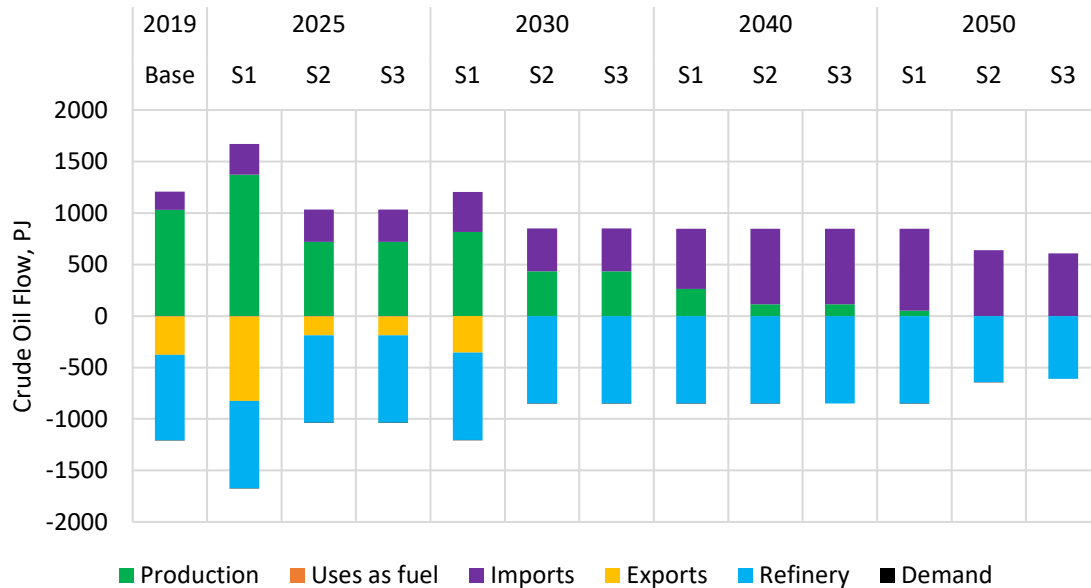
Note: Since for scenarios S2 and S3, the oil production plummets to zero by the year 2050, so does the COTNGPR.

The crude oil balance for the updating (S1), upgrading (S2), and inflection (S3) scenarios are shown in Figure 12. Even though the refinery's throughput decreases by 23% and 27% regarding the base year load for the S2 and S3 scenarios for the year 2050, more than the domestic crude oil production is needed to feed these facilities. The national crude oil production gradually declines over time and must be imported. Thus, by 2030, the imports

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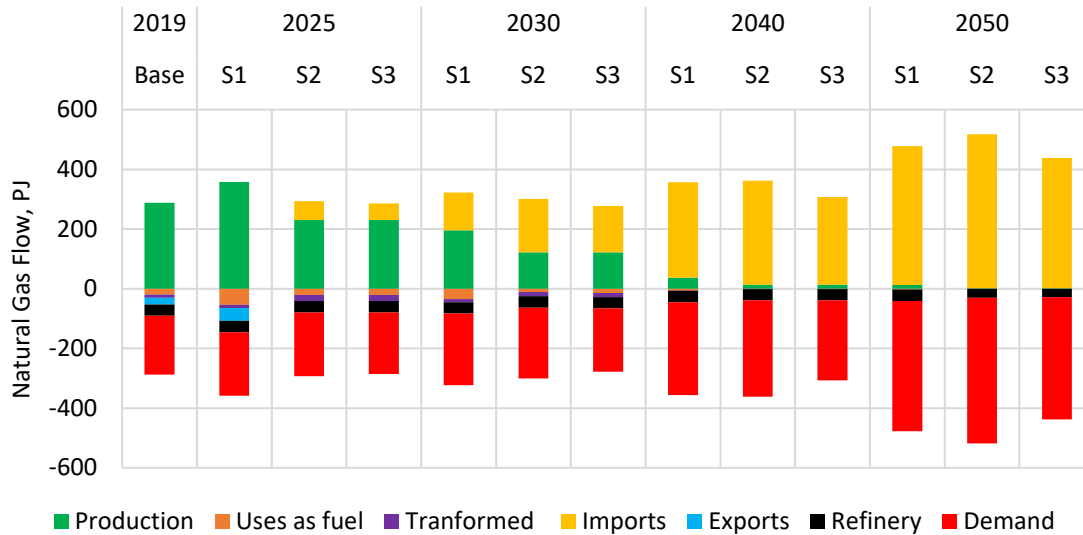
will be greater than exports, representing 46 % and 49% of the demand for crude oil for the medium supply (S1) and low supply (S2 and S3) scenarios. It should be noted that crude oil can be imported or exported depending on its demand at the refineries, given by its physical-chemical characterization, such as the API gravity (see Appendix A, section 4.1).

Figure 12. Balance of crude oil in the TIMES-O&G model



The demand for natural gas for the consumption and refinery sectors increases to 102%, 120%, and 80% from 2019 to 2050 in scenarios S1, S2, and S3, respectively (see Figure 13). Like crude oil, natural gas production declines. Thus, by 2030, natural gas imports will be about 46%, 65%, and 62% of the supply for scenarios S1, S2, and S3, respectively, and by 2050, this percentage increases to 98 % for scenario S1 and 100% for the other two scenarios, which implies that in the long term, it will not be possible to export natural gas. The unfavorable balance of trade for the natural gas means a higher supply cost for the O&G company, especially in the long term, in which the company would only play the role of import agent and not hydrocarbon producer, since by 2050, practically the entire crude and natural gas demand is supplied through imports.

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Figure 13. Balance of natural gas in the TIMES-O&G model

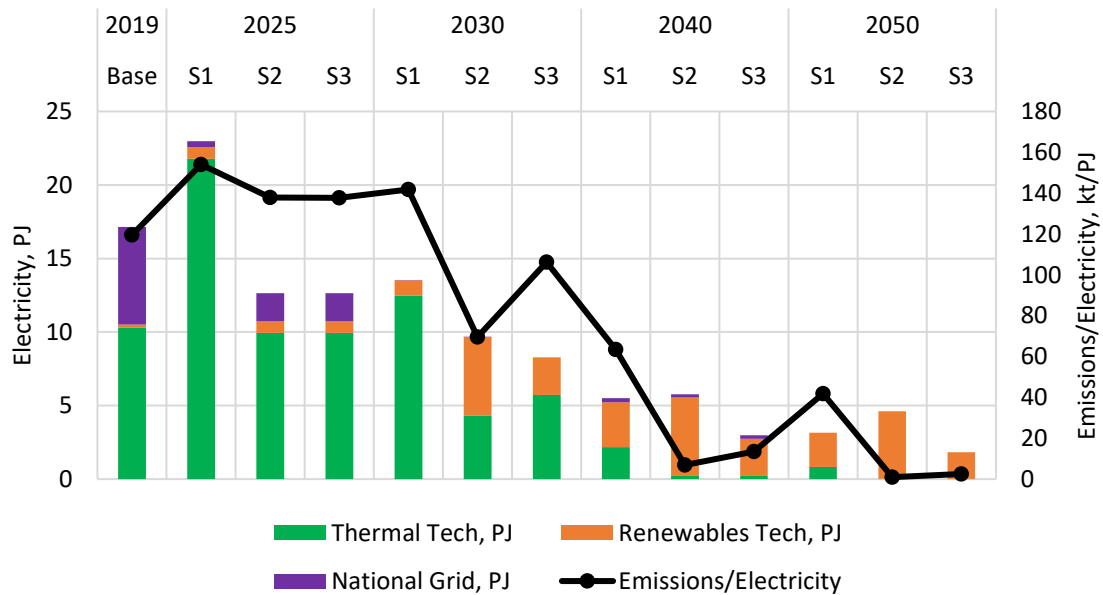
3.3.3 Consumption and production of electricity

As hydrocarbon production decreases, so does its transport capacity; consequently, the electricity demanded also does so. The energy matrix comprises thermal processes from natural gas, crude and fuel, renewable energy (solar, wind), and purchases from the national grid. In the base year, 58% of the electricity demand is self-generated, and the grid generates the rest. According to the results, the company seeks to completely self-supply the electrical demand of its processes over time, reducing purchases from the national grid until 2030, when they are approximately nil. Also, the penetration of renewable energies is observed over time, from 1% in the base year to 8%, 55%, and 31% in 2030 for scenarios S1, S2, and S3, respectively; eventually, in the long term, renewable energies would generate 73% (S1) and 99% (S2 and S3) of the electricity requirements for production and transport processes. However, it is highlighted that this also occurs because the electricity demand decreases to such an extent that the installed capacity of renewable energy is sufficient. The participation

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of renewable energies not only causes the rate of emissions from electricity generation to decrease over time but also provides fossil fuels traditionally used for self-generation to meet demand.

Figure 14. Generation of electricity for production and transportation stages.



3.3.4 Balance of fuels

The results in Figure 15 show that the O&G company, unlike its role as a long-term producer of hydrocarbons, would be an essential refining agent in the Colombian market since the loads to refineries are maintained. The fuel production is optimized to meet the national demand and export surpluses of the most valuable products. Indeed, the combined output of gasoline and diesel remains at around 74% throughout the time horizon except for the year 2050 in scenarios S2 and S3 because the demand for gasoline and diesel decreases by 14% and 18% compared to the base year in scenarios S2 and S1, respectively. Besides, under the current conditions of prices and output compositions, it is profitable for the company to import crude and refine it to obtain liquid fuels demanded in Colombia instead

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of directly importing them, so refining activity remains at maximum capacity in the three scenarios. However, suppose the demand for fossil fuels decreases below the country's refining capacity (scenarios S2 and S3 in 2050). In that case, crude oil imports will be carried out to the extent that the demand for fossil fuels can be supplied, which implies that the maximum refining capacity will not be used; in other words, it is not profitable to import the raw material for refining and then export these fuels.

Figure 15. Production of fuels in both refineries in the TIMES-O&G model

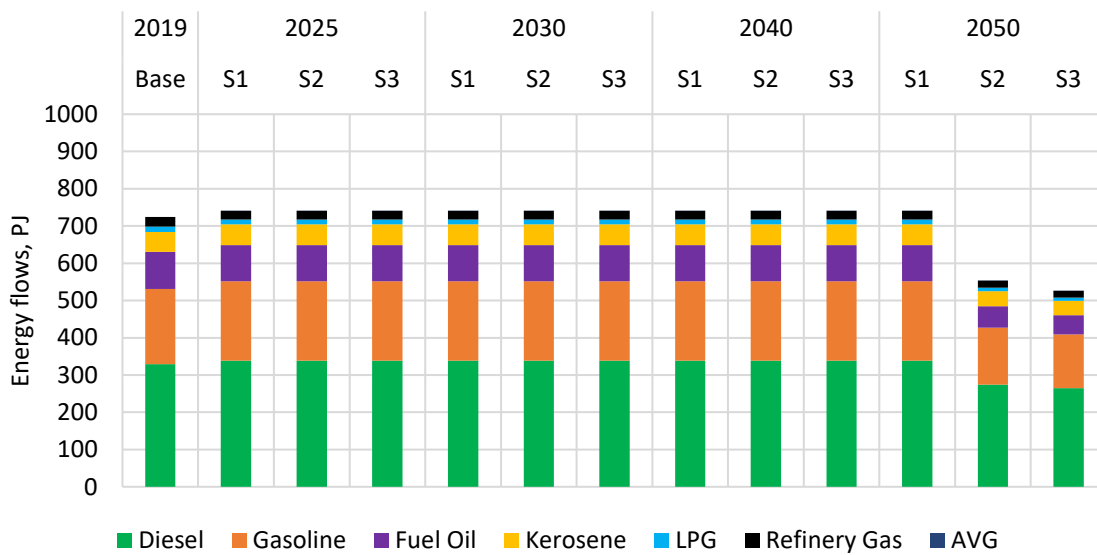
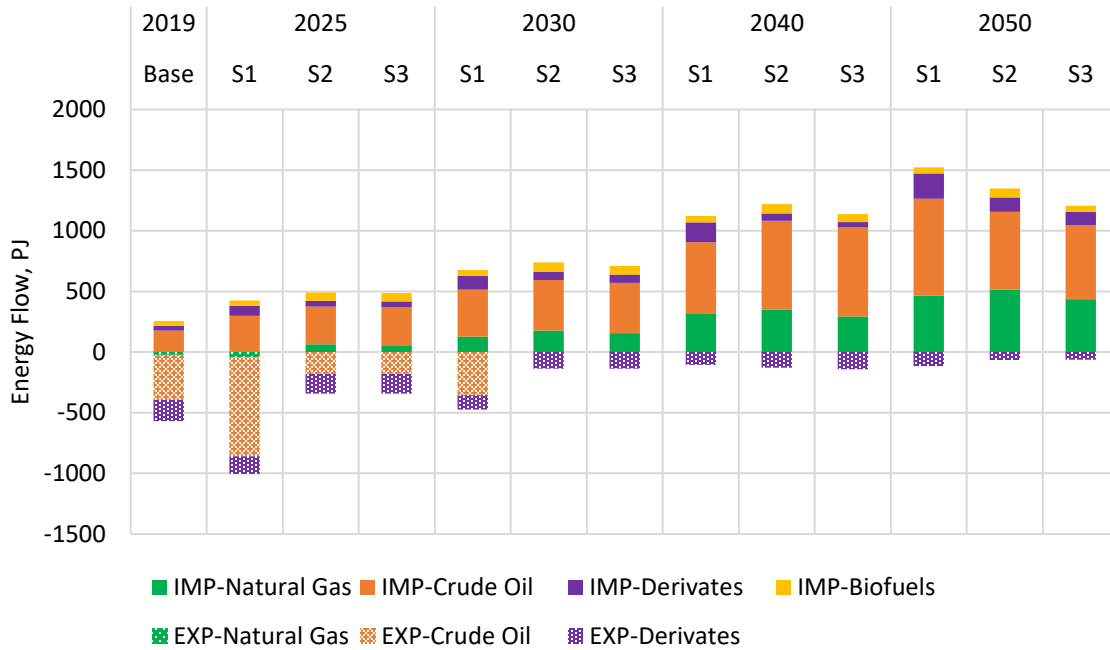


Figure 16. Energy flows for export and import processes. Figure 16 presents the trade balance of commodities. It is highlighted that in the base year, for every 1 PJ of imported crude, 1 PJ of derivatives is exported. In contrast, by 2050, for every 1 PJ of imported crude, 6.87, 9.85, and 9.84 PJ of products are shipped in scenarios S1, S2, and S3, respectively, which reinforces the hypothesis that the O&G company in the medium and long term would act as an importer of primary energy sources (oil and natural gas) for further transformation at the refineries to meet the fuel demand of the Colombian sectors. Shows the economic impact of the trade balance in terms of costs. For the base year, for every 1 MUSD spent on

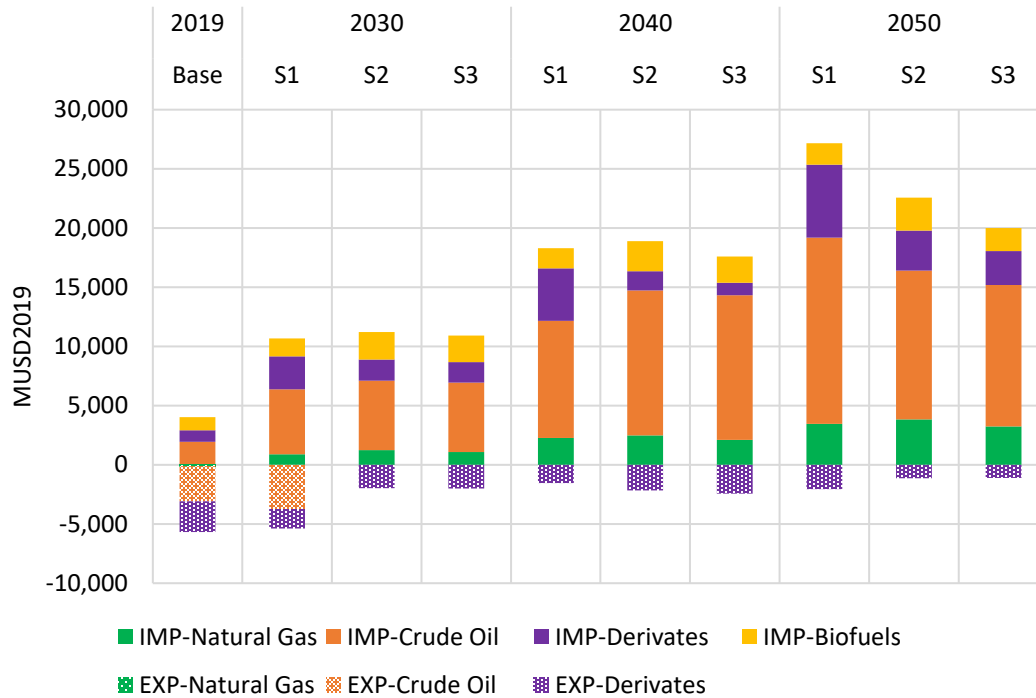
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imports, the O&G company obtained 1.41 MUSD from exports. However, this positive trend annually decreases until the year 2050, where for each 1 MUSD spent on imports, the company only gets back 0.08, 0.05, and 0.06 MUSD in scenarios S1, S2, and S3, respectively.

Figure 16. Energy flows for export and import processes.



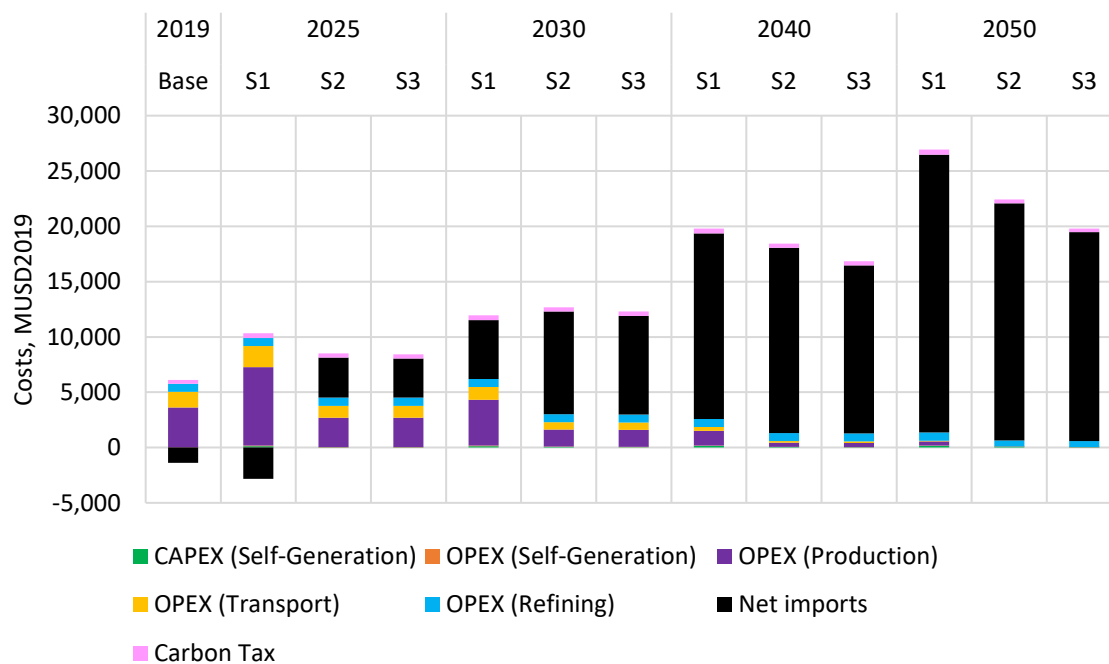
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Figure 17. Balance of cost of import and export processes

3.3.5 Cost of the system

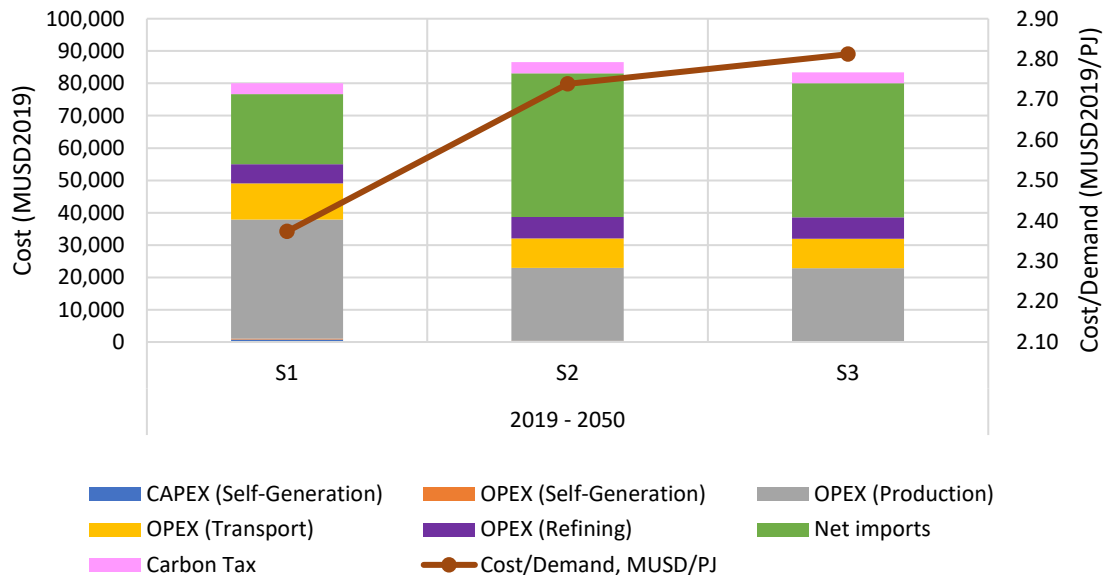
Similarly, it can be seen in Figure 18 the evolution of system costs to meet the demand of consumer sectors. For the base year and scenario S1 in 2025, net imports are harmful - that is, exports are more significant than imports – leading to a cost reduction of 29% and 38%. On the contrary, for scenarios S2 and S3, from 2025 on, the net imports are positive (unfavorable balance of trade), representing 42 and 43% of the total cost. Eventually, by 2050, imports represent 93, 96, and 95% of the system's total cost for the three scenarios. This also reinforces the hypothesis that the company is an import agent that refines primary materials to meet national demand.

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Figure 18. Annual costs to supply national fuel demand.

The TIMES-O&G model is demand-driven, which implies that for each scenario, the O&G company optimizes the system's total cost (TCS) subject to meet the national energy demand. For this reason, the minimum TCS for each scenario is selected as a comparison criterion between them. Thus, the best scenario for the O&G company is S1 because it considers more hydrocarbon reserves - which implies decreased import costs of hydrocarbons - than scenarios S2 and S3. As a result, the TCS is reduced by 15 % and 18 %, respectively. In scenario S1, the cost of imports represents 27 % of the TCS, while in scenarios S2 and S3, this figure rises to 50 % and 51 %, respectively. Since the TCS of scenarios S2 and S3 depends mainly on imports and both scenarios assume the same crude oil production potential - which in turn represents approximately 27 % of the system cost -, the difference between both scenarios is only 2.7 % (0.07 MUSD2019/PJ), see Figure 19.

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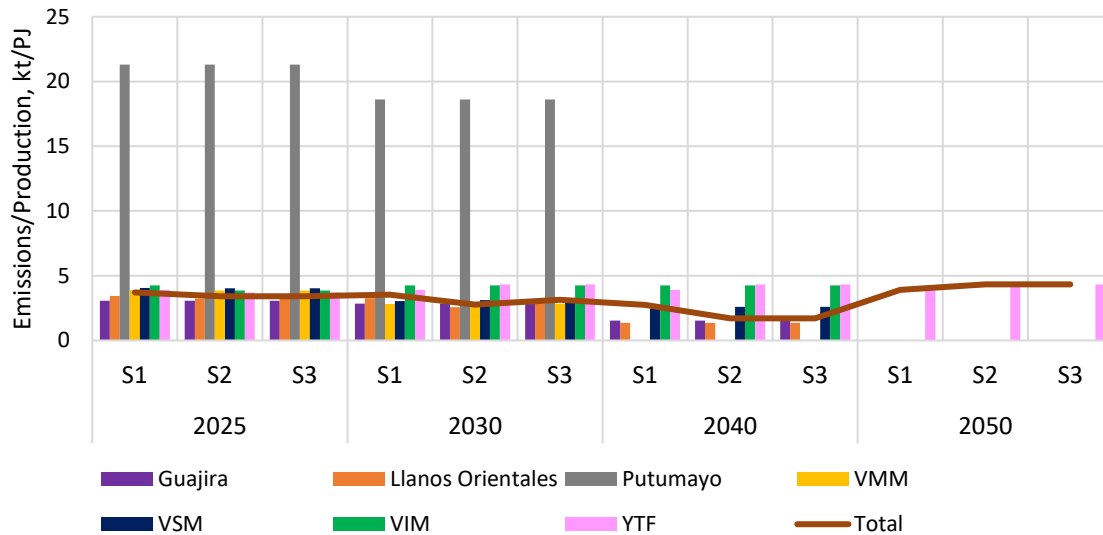
Figure 19. Annual calculated system cost by 2050.

Note: cost data is already discounted.

3.3.6 GHG emissions

Emissions from the production and transportation sector vary depending on how the electricity is produced (fossil fuel, renewable energy, or grid purchases). Estimating the intensity of emissions (IE) helps identify which sedimentary basins deserve more attention in decarbonization. The Putumayo basin has about four times the IE company average. All the gas produced in this basin is burned (see Appendix A, section 3.3); these operations represent 77% of the total emissions from this oilfield in the base year, increasing to 89% at the end of the productive life.

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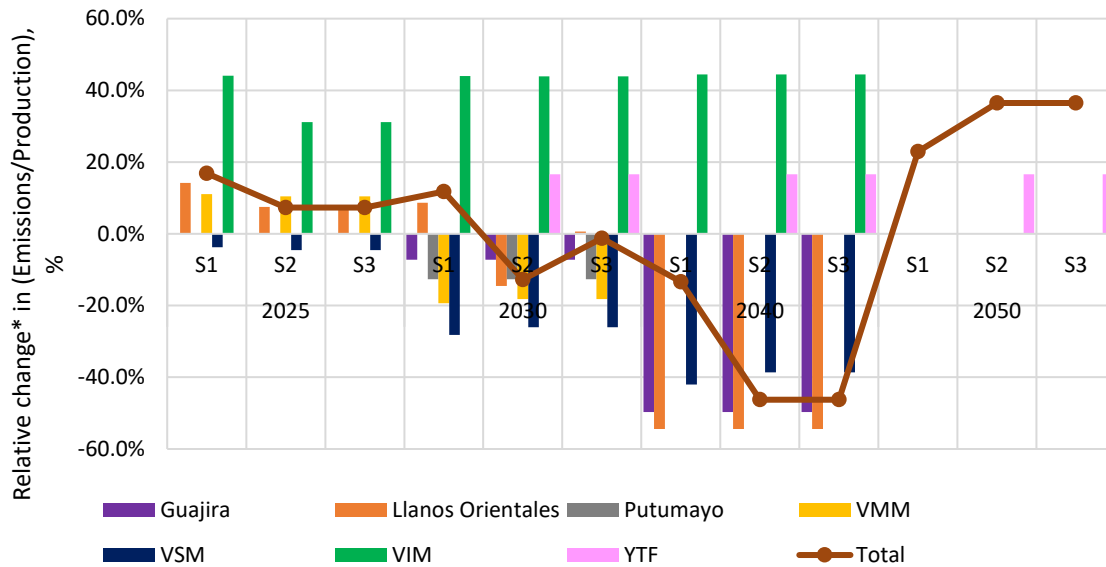
Figure 20. The intensity of emissions in production and transportation the stages.

The IE of the production and transport stages is shown in Figure 21. By 2030, the IE for all the oil fields will decrease except for the VIM and YTF basins. In both cases, the electricity generation from the grid is replaced by thermal generation – which has a higher emission factor than the national grid -. In the case of the VIM basin, in the base year, 97% of the electricity is purchased from the grid, while by 2025, the participation of thermal generation is 100%. In the case of discoveries, in scenario S1 - under an assumption of medium supply - electricity generation is based solely on natural gas (Combined Cycle technology) and remains constant throughout the period, while in scenarios S2 and S3 - with assumptions of low production potentials - investment in self-generation capacities is also focused on natural gas (Combined Cycle technology), but to a lesser extent, thus in 2025, 42% of electricity is purchased from the national grid and in 2030 participation is null; the preceding has an environmental implication since the emission factor of the national grid is lower than that of CC technologies, therefore the IE increases in scenarios S2 and S3. Regarding the IE of the company, it can be noted that there would only be a decrease in the

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three systems by 2040, but it must be recalled that the production for this period is only 23% (S1) and 10% (S2 and S3) compared to the base year.

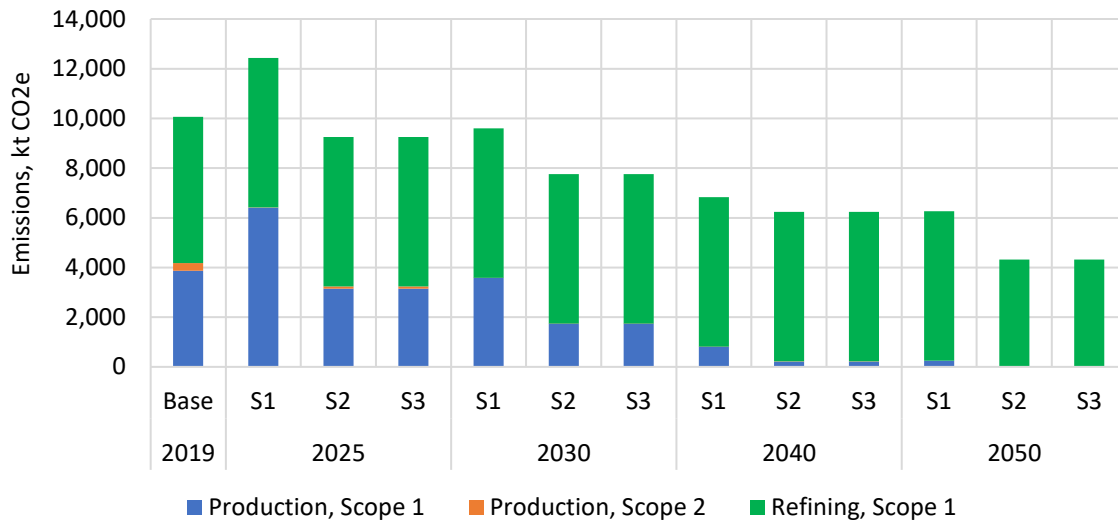
Figure 21. Evolution of the IE in production and transportation stages.



Note: *the relative change is calculated based on the first year of production: 2019 for O&G company, Eastern Plains (LLO), Putumayo, VMM, VSM, VIM; 2020 for Guajira; 2025 for YTF.

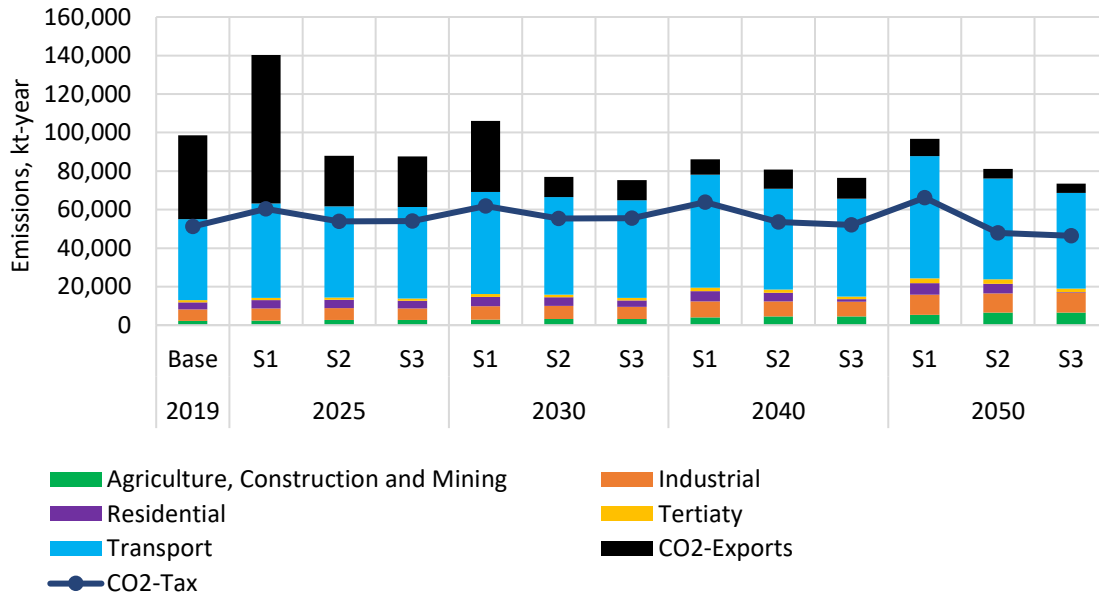
Figure 22 shows the emissions in kt CO₂-eq for each sector of the oil & gas company considered in our model and the scope of the emissions. It can be seen that the magnitude of emissions from the production stages decreases over time, but the same does not happen with the intensity (see Figure 21). On the other hand, the emissions from the refinery stages will represent at least 88% (S1) and 97% (S2 and S3) of the company's total emissions in 2040 due to the drop in oil and gas self-sufficiency. For this reason, refinery decarbonization strategies should be the primary objective since they represent at least 55% of the company's total emissions, even for the base case.

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Figure 22. Emissions from each stage and scope.

Finally, the scope 3 emissions of the O&G company also demonstrate that exports decrease over time, going from 44% in the base year to 9, 6, and 7% for scenarios S1, S2, and S3, respectively. Regarding the carbon tax, in the base year, the emissions covered by this tax represent 93% of the total emissions of the consumption sector - the carbon tax does not cover exports -, but in the long term (2050), this rate would only cover 75%, 63%, and 67% of the emissions for national consumption; this would imply a relief for the company to the extent that the cost of the system for this tax would be lower; Despite these, the participation of this rate in the price is only 4.4%, 4.1% and 4.2% for scenarios S1, S2, and S3 respectively.

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Figure 23. Emissions from Scope 3**3.4. Summary of the chapter**

This study analyzed the role of a conceptual O&G company in Colombia's energy vision proposed in the National Energy Plan 2050 and its implications. We developed a TIMES-O&G model representing typical oil and gas company operations. The model was tested by analyzing the impact of the Colombian energy planning scenarios on the hydrocarbon sector (company, oil fields, or refineries detail) and the TIMES-O&G model.

The results show that even with medium hydrocarbon supply scenarios (S1), the self-sufficiency in the medium and long term for the O&G company is in doubt since in 2030, imports of crude oil and natural gas will correspond to 46% of the demand (both, the company and Colombia demand). This is accentuated in scenarios of low supply (S2 and S3), in which imports represent 54% and 49% of total demand, respectively. This trend is maintained in the long term until 2050, when imports of crude oil and natural gas supply 92% and 100% of the demand in the best scenario (S1), respectively. Despite this, the operation of the refineries

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will continue at their maximum operational capacity, except for 2050, when the throughput will decrease by 14% and 18% in scenarios S2 and S3, respectively –note that in scenario S1, this decrease was not observed-. Under these scenarios and their assumptions, the O&G company will lose its role as a producer of hydrocarbons in Colombia. It would run the risk of becoming only an importer of primary energy for refining, thus supplying the Colombian market with secondary energy sources in the long term.

The self-sufficiency of hydrocarbons for the O&G company has important economic implications. In the short and medium term, the consideration of scenarios of medium reserves (S1) in contrast to those of low reserves (S2 and S3) will represent an economic benefit for the company by lowering the cost of the system through exports until 2030, which allows the system cost of the entire horizon analyzed to be reduced by 15% and 18% compared to scenarios S2 and S3 respectively. The economic consequences are accentuated in the long term because, by 2050, the imports will represent 93, 96, and 95% of the system's total for scenarios S1, S2, and S3, respectively.

Decarbonizing the production and transportation sectors will require more significant efforts since, in the three scenarios proposed, without considering CCS options or improvements in efficiencies—as is the case of this study—it is not possible to reduce the intensity of emissions until 2040. Refining operations will be increasingly important in terms of costs and emission intensity in any system, so it is recommended that this industry's decarbonization and improvement pathways be reviewed.

Additional studies should focus on evaluating the addition of new resources, decarbonization routes for the production and refining sector, and the role that the O&G company can play in the hydrogen market at the Colombian level.

4. Evaluation of the integration of a conceptual O&G company in a disruptive scenario in terms of decarbonization

4.1 Introduction

Anthropogenic GHG emissions have caused global warming of 1.0 C above pre-industrial levels (IPCC, 2014, 2018). If the trend continues, the planet's temperature will reach 1.5 C between 2030 and 2052, which will have irreversible consequences for human and natural systems (IPCC, 2018, 2022). The Paris Agreement can play an essential role in the fight against climate change since each member -currently, 196 parties have adopted this agreement- must establish their Nationally Determined Contributions (NDCs), which are the strategies and actions that they will take to reduce their emissions GHG (UNFCCC, 2023).

Energy system models (ESMs) are mathematical representations of energy systems that have made it possible to establish empirical evidence that helps decision-making. These ESMs aim to explore and contrast scenarios, including GHG mitigation routes and objectives at the global, regional, national, or local level (Chang et al., 2021; Giannakidis et al., 2015, 2018).

In addition, it is possible to evaluate if the stated policies and announced pledges - including those communicated in the NDCs but much more besides- are sufficient to achieve a particular goal (IEA, 2022). According to the IEA (2021b), in the stated policies scenario (STEPS), emissions in 2050 would increase by 5.8% -to 36 Gt CO₂-eq-, while if all national pledges regarding carbon neutrality (APC) were met, emissions in 2050 would decrease by 64.7% -to 22 Gt CO₂-eq-, and if the trend continues after 2050, the surface's temperature will increase to 2.1 C in 2100. Recently, Panos et al. (2023) carried out a study in which they

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analyzed more than 4000 scenarios of the world's energy system and found that in more than 70% of these, the limit of 1.5 C would be exceeded this decade, which implies that mitigation efforts must be reinforced starting immediately.

On the other hand, it is expected to define a scenario with a desired output to explore the possible routes and what is needed in each energy system sector and actor to reach this goal. Summarizes the main insights of the actions required to reach net zero in 2050. Table 4 summarizes the central insights of the actions needed to reach net zero in 2050 (DNV, 2021; IEA, 2021c; IRENA, 2021b): despite population growth, total primary energy supply and final energy consumption in 2050 decreases from the values reported in 2021 (624 EJ and 439 EJ respectively), representing efficiency improvements and changes in consumption behavior; The energy mix must transition from a fossil fuel controlled - the fossil fuels share in 2020 was about 80% (IEA, 2021c)- to a clean energy diversified one; the electricity sector must achieve carbon neutrality after 2040, with renewables accounting for more than half of the share of generation by 2030 and around 90% in 2050; demand from the transport sector should decrease by 2050 - peaking by 2030 at the latest- and the current share of fossil fuels in this sector -which represents around 90% today (IEA, 2023h)- should decrease as clean energy such as electricity, hydrogen and biofuels are widely used; low-emission hydrogen production can aid decarbonization by providing flexibility for specific energy systems; carbon capture, utilization and storage can facilitate the transition to carbon neutrality by removing emissions from existing energy systems in sectors that are difficult to decarbonize and by scaling up low emissions hydrogen production rapidly.

Although there are different decarbonization routes, most economic and energy models agree that decarbonization rests on four pillars (Fay et al., 2015): decarbonizing the production of electricity, undertaking the massification of electricity and switching to cleaner

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fuels, improving efficiency, and preserving and increasing natural carbon sinks through improved management.

Aligned with these pillars, developing a portfolio of decarbonization technologies is necessary. In the 4,000 scenarios analyzed by Panos et al., (2023), none of them relied solely on a single mitigation option but critical technologies -such as hydrogen and synthetic fuels, CCS, and Direct Air Capture with Sequestration, renewable energies, and bioenergy- play complementary roles in climate change mitigation. Likewise, the IEA (2020a) establishes that the transformation of the power sector will not be able to achieve carbon neutrality on its own. Instead, the combination of electrification with CCUS, bioenergy, and hydrogen could contribute to more than half of the reduction of emissions accumulated in the energy sector in the period 2020-2070.

Table 4. Insights of scenarios of net zero pathway scenarios.

Sector	Indicator	Reference year	DNV (2021)	IEA 2021b)	IRENA (2021b)
Global	Total primary energy supply	2030	600 EJ/y	550 EJ/y	590 EJ/y
		2050	570 EJ/y	550 EJ/y	614 EJ/y
	Share of fossil fuels in total primary energy supply	2050	23%	20%	26%
	Total final energy consumption	2030	445 EJ/y	390 EJ	373 EJ/y
2050		399 EJ/y	340 EJ	348 EJ/y	
Power sector	Electricity share in TEFC	2030	13%	17%	30%
		2050	51%	50%	51%
	Reach carbon neutrality	-	2046	2040	-
	Share of renewable energy in power generation	2030	57%	61%	65%
2050		90%	88%	90%	

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	Demand	2050	it declines 45%	it declines 30%	it declines 24%	
	Peak of consumption	-	2025	2025	2030	
Transport sector	Share of electricity in consumption	2050	52.1%	45%	49%	
		2030	-	15%	13%	
	Blending with biofuels	2050	-	15%, and it could increase for the aviation sector		25%
Hydrogen	Share of hydrogen in the TEFC	2030	-	4%	3%	
		2050	14%	13%	12%	
	Production of hydrogen	2030	Around 33 EJ/y	Around 25,2 EJ/y	28.5 EJ/y	
		2050	around 70 EJ/y	around 60 EJ/y	73.6 EJ/y	
CCS	Removal	2030	4.6 Gt CO ₂ /y	1.6 Gt CO ₂ /y	-	
		2050	5.8 Gt CO ₂ /y	7.6 Gt CO ₂ /y	7.9 Gt CO ₂ /y	

Since the energy models seek to explore all the sectors and actors in the energy system, the conclusions in specific sectors may be general. For example, although it is established what the production of low-emission hydrogen should be, it is not clear who could be the main actors in this energy system and whether companies from the O&G industry, which currently uses this hydrogen in refining stages, can be found among them.

In a carbon-neutral scenario in which the share of fossil fuels in 2050 is less than 26%, it is not clear what the role of the O&G industry will be in the energy transitions. This study aims to evaluate the role of a conceptual company dedicated to the O&G sector in Colombia in the energy transition through a TIMES-O&G model, an energy system model specially built to represent this company. Likewise, this company's objective is to analyze the possible

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decarbonization routes of the primary operations of the O&G company to align with the emission mitigation goals by 2050.

4.2 Emissions of O&G industry

The emissions of the O&G industry are usually divided into three categories: Scope 1 covers direct emissions generated by O&G operations (production, transportation, and processing); Scope 2 refers to indirect emissions, which are normally associated with the purchase of energy for use in O&G activities; and finally, scope 3 groups emissions from the final use of hydrocarbons.

Scope 3 emissions are generally the most representative of the O&G industry. According to IEA (2023a), depending on the type of company (Majors, independents, international national oil companies, national oil companies), scope 3 emissions represented between 73%-81% of total oil emissions (scope 1+2+3) in 2018; likewise, in the case of natural gas, scope 3 represented between 65%-81% for the total in the same period. Similarly, Wood Mackenzie (2022) reports that Scope 3 emissions represent between 80-95% of the total emissions from the O&G industry.

Despite this, all the scopes have particular relevance in global emissions. The US EPA (2010) reports that scope 1 and 2 emissions represented 15% of the global emissions GHG in 2010, while this percentage was quantified at 9% by Beck et al. (2020) in 2015 and at 15% by IEA (2023a) in 2018. On the other hand, emissions from scope 3 account for 38% and 40% of total emissions in 2015 and 2028, respectively (Beck et al., 2020; IEA, 2023b).

Recently, certain O&G companies have announced targets or commitments to reduce their emissions in two approaches(IRENA, 2021a): the first is called the intensity approach

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and is related to direct and indirect O&G operations (scope 1 and 2). In contrast, the second is called the absolute approach and contains all emissions from the hydrocarbon value chain (scope 1 +2 +3). IRENA (2021a) analyzed the commitments acquired -as of January 2021- by seven O&G companies that constitute around 18% of world production (BP plc, Chevron Corporation, Eni S.p.A., Equinor ASA, ExxonMobil Corporation, Royal Dutch Shell plc, Total SE) and that five of these have commitments from the absolute approach, while the remaining two have intensity approaches (ExxonMobil Corporation and Chevron Corporation). Similarly, Wood Mackenzie (2022) analyzed more than 120 O&G companies and estimates that 65% of companies have defined carbon neutrality targets with an intensity approach (scopes 1 and 2), while only ten companies have committed to absolute carbon neutrality (scope 3).

Although achieving carbon neutrality in scopes 1 and 2 for O&G companies is beginning to become standardized, it has two problems regarding the fight against climate change: first, a maximum reduction of 15% of total global emissions -related to scopes 1 and 2- (IEA, 2023b) would be achieved if decarbonization of all the activities of the O&G industry, which is not enough by itself to comply with the goal of the Paris Agreement. On the other hand, reducing emissions from direct and indirect activities does not mean that the share of hydrocarbons in the energy mix decreases (IRENA, 2021a) as it should, according to carbon neutrality scenarios (see Table 4).

The task of decarbonizing scope 3 emissions is challenging and implies profound changes in the structure of O&G companies, primarily through three pillars reported by Wood Mackenzie (2022): expansion towards new low-emission energy sources as part of the business; an expansion aggressive use of technologies such as CCS and other technologies

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to remove carbon and use it for different processes; and diversify the portfolio towards more sustainable end-use fuels.

Undoubtedly, external pressures from the market, government, and investors can favor the conditions to achieve absolute carbon neutrality for the O&G industry (IEA, 2023b; Jain & Palacios, 2023; Johnston et al., 2020). Although clean energy investment has a 1.5 to 1 ratio compared to fossil fuels, this ratio needs to increase to 9 to 1 by 2030 to be consistent with carbon neutrality scenarios (Jain & Palacios, 2023). Similarly, the O&G industry has begun to invest in technologies necessary for carbon neutrality -such as biofuels, CCUS, and renewable energy-, going from 0.5% in 2015 (1.5 USD billion) to 0.9% in 2019 (2.1 USD billion) (IEA, 2023b), but this should increase considering that the IEA (2021b) estimates that by 2030 it is necessary to have a portfolio that could cost 90 billion dollars, while currently only a budget of 25 billion dollars is available.

Thus, in a decarbonization scenario, O&G companies should try to reduce the intensity of their emissions and products while seeking to fit into the future energy context. According to the IEA (2021b) net to zero scenario, current world oil and natural gas production in 2050 will fall by around 75% and 55% in 2050, respectively, in the way that new explorations for new resources beyond those already approved will not be required, even so, the investment of current assets must continue.

4.3 Decarbonization pathways for the O&G industry

According to the IEA (2021b), the strategy of decarbonizing the direct and indirect operations of the O&G industry is the most viable and cheapest option concerning scope 3 emissions; it is estimated that 15% of the industry's net income in 2022 would be enough to carry out the 50 and 55% reduction in the intensity of emissions from oil and natural gas

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operations respectively in 2030, which in turn is the path estimated by the IEA in the net to zero 2050 report. Below are the main decarbonization paths to an O&G company reviewed in this study, including those considerations outside the company's scope of action but representing external pressures for reducing scope 3 emissions (named as environmental policies).

4.3.1 Renewable energy

The entire hydrocarbon value chain requires energy, of which close to 90% is provided by fossil fuels themselves. In comparison, the remaining 10% comes from electricity purchased from the grid or self-generated used primarily fossil fuels (Halabi et al., 2014). However, the electrification of specific processes and the integration of renewable energy in a generation is possible significantly when the prices of these latest technologies have declined in the last decade -e.g., the levelized cost of electricity for solar PV and Wind technologies decreased by 86% and 67% respectively between 2009 and 2017 (Lazard, 2017)-.

Different reports have identified some of the potential applications of renewable energy in the O&G industry, such as (Ericson et al., 2019; Halabi et al., 2014; McKinsey & Company, 2020): generating electricity for the consumption of primary recovery operations - artificial lift system requirements - and secondary - injection system requirements; supply the necessary energy to generate steam on site that is used for thermal recovery; to generate electricity for water treatment and desalination processes; electrification of natural gas and oil transportation systems; generate electricity so that it can be used for the production of hydrogen; electrification of process to generate steam.

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Elgqvist et al. (2022) analyzed the integration of renewable energies in O&G operations. They found that smaller technologies are the most cost-effective and that under a carbon tax of 7 USD/t CO₂, renewable energy technologies could generate up to 50% of the site's load. Korpås et al. (2012) studied the possibility of integrating offshore wind farms to meet the demand for electricity from oil and gas rigs. They found that these technologies can penetrate current generation systems -based on natural gas- by up to 40%, representing cost savings in electricity generation. Zheng et al. (2023) evaluated the development of a microgrid system for underground in-situ electrical heating for oil shale extraction due to its high electricity requirement and found that if the microgrid system included a combination of renewable energy (solar PV) with a 41% share it can reduce the annual cost of the system by 11% compared to using a system based only on conventional sources (diesel); in addition, the latter system can increase its cost by 58.5% if the price of fuel is doubled.

However, the integration of renewable energies in the O&G industry must face challenges such as (Ericson et al., 2019): reliability to operate in a wide range of scenarios that include extreme conditions in some cases; minimize the effect of variability in generation or include storage systems since O&G process operate 24/7 regardless of weather conditions. Other reports argue that renewables may not be the most daring option for decarbonization. Jarboui (2021) analyzed the operative and environmental efficiencies of 45 US oil and gas companies and established through a True Fixed Effect model that renewable energies and biomass energies contribute to improving the ecological efficiency of companies. Still, at the same time, they can contribute to increasing the inefficiency of operations. Janzen et al. (2020) used a LEAP model to analyze the 2019-2050 horizon and explore the abatement potential and costs of integrating renewable energy and low-emission energy in the Canadian oil sands and across the 27 scenarios they analyzed, the results show that solar and wind

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energy did not penetrate the market, while other technologies such as small nuclear reactors, geothermal energy, bioenergy, and hydropower could reduce emissions by up to 133 Mt CO₂-eq cumulative emissions for 6 t/ CO₂-eq under the scenario with higher incentives (50 USD/t CO₂-eq).

4.3.2 Biomass uses and biofuels

Currently, 40% of bioenergy is used in the traditional use of biomass for cooking. However, to achieve carbon neutrality, it is necessary to transition towards the use of modern forms of solid biomass that can reduce emissions in the electricity and industrial sectors. This will imply that supply needs to increase 2.5 times between 2020 and 2050 (IEA, 2021c).

According to the IPCC, the electricity sector must use low or zero-emissions technologies, including biomass. However, the impact of this energy to reduce emissions will depend on the scale of development, the technology, and the supply chain—biomass production (IPCC, 2022). The efficiency of electricity generation using biomass will depend on the technology and type of biomass used, the scale, and its application (Rosendahl, 2013); the most common technology for generating electricity in industrial applications, using biomass is direct combustion, that uses it as fuel and produces power and heat (Bhuiyan & Naser, 2015; Rosendahl, 2013). One of the attractions for the penetration of biomass in the electricity sector is that it is considered that the carbon dioxide emitted is the same as that which is absorbed during the growth of biomass (Marangwanda et al., 2020). Furthermore, according to the IEA, bioenergy with carbon capture and storage (BECCS) plays a critical role in carbon neutrality by achieving even harmful emissions, especially in sectors where this is difficult to achieve (IEA, 2021c).

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Another possible use of biomass is the integration with existing refineries through a co-processing route, which may affect reducing (to a small extent) the demand for crude oil loading to the refineries and decarbonizing the existing refineries (van Dyk et al., 2019; Younis et al., 2023). Additionally, recent regulatory progress has been made, as ASTM 1655 now allows the co-processing of lipids at 5% blends in existing refineries (Van Dyk et al., 2019). Although there are different technological options for co-processing (especially for hydrotreating units and Fluid Catalytic Cracking), the high cost or technological challenges have limited its development (van Dyk et al., 2019; É. Yáñez et al., 2021).

Another essential role of biomass focuses on producing biofuels for the transportation sector since the latter represents about 16% of GHG emissions in 2020 (Our World in Data, 2020). In 2022, biofuels represented about 3.5% of global demand in the transportation sector, with an increase of 6% between 2016 and 2022. However, to achieve carbon neutrality, it is necessary that in 2030, biofuels supply 9% of global demand in this sector (IEA, 2023a). To achieve this, the percentage of blending (ethanol with bioethanol and diesel with biodiesel) must increase as follows (IEA, 2021c): for road transport from 5% (current value on average) to 13% in 2030 and 41% in 2050; for aviation, the implementation of sustainable fuels must begin, then the biofuels share reaches 45% in 2050. However, the current demand for biofuels is focused only on the 4th market (the United States, Europe, Brazil, and Indonesia), so policies to accelerate the use of biofuels must be extended to other markets (IEA, 2023f).

In the Colombian context, according to National Energy Plan (UPME, 2020b), the participation in the primary supply 2050 of biomass, waste, and biofuels will represent between 9% (disruptive scenarios) and 11% (updating and upgrading scenario). However, the supply of this energy group only increases by 7% between the period 2050 and 2019 in the

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BAU scenario, while in the remaining three scenarios, the supply remains constant or decreases by up to 10%. The above is mainly because, in the disruptive scenarios and inflection, the projection of the demand for gasoline and diesel decreases. Therefore, the consumption of biofuels (ethanol and biodiesel, respectively) also decreases. In contrast to the decrease in the demand for biofuels, biomass and waste continue to be relevant for decarbonization scenarios since, in all scenarios, the installed capacity used by these commodities goes from 6 MW in 2019 to 401 MW in 2050 in the updating and upgrading scenarios and can reach up to 2000 MW in the disruptive scenario.

Yañez establishes that co-processing routes in the Colombian context can contribute up to 19% of total biofuel production and capture 10% of emissions if combined with CCS technologies (Younis et al., 2023). In another study, É. Yañez et al. (2022) establish that the co-processing options account for around 60% of the mitigation options portfolio for an existing refinery.

Colombia is one of the countries that has fully implemented the use of biofuels, currently regulated through resolutions 40666 and 40730 (MINMINAS, 2019; Resolución 40730 de 2019, 2019), which estimated 10% by volume for both ethanol and biodiesel. A report of the IEA TCP Bioenergy (2023) highlights that the use of biofuels contributes to a significant reduction in greenhouse gases in the case of Colombia as well as other countries such as Argentina, Brazil, and Guatemala.

4.3.3 Value chain of hydrogen

The IPCC (2022) mitigation of climate change report highlights the importance of hydrogen on the path to decarbonization of the energy sector, as long as the hydrogen is produced using renewable energy sources or under technology that makes it low in emissions.

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As mentioned in Table 4, hydrogen will replace fossil fuels to a certain extent in different uses, especially in transportation, industry, and chemicals (DNV, 2021; IEA, 2021c; IRENA, 2021b).

In addition, hydrogen can be mixed with natural gas in a certain percentage to prevent severe effects on integrity (ENTSOG, 2019; IEA TCP Bioenergy, 2022). According to HyBlend (2022), it can theoretically be up to 30%. Still, applications in natural environments (Capelle-la-Grand in France and Keele University in the UK) have only achieved a mixture of 20% (IEA, 2021a). The above has advantages such as the mixture can be used by existing devices; use the existing infrastructure (gas pipelines) to transport the mix, since the cost to transport and distribute H₂ through pipelines is higher compared to natural gas, according to the IEA (2021) the CAPEX of pipes of the same diameter for H₂ is between 10-50% higher compared to a gas pipeline. However, when the H₂ is mixed with natural gas, the energy density of the mixture decreases since the Energy density of hydrogen is about a third of natural gas (Qadrnan et al., 2015); then to meet the demand, a greater injection flow of the mixture will be required.

In 2022, the global use of hydrogen was around 95 Mt, of which 43% was used in refineries and 57% in industries, mainly to produce ammonia and methanol (IEA, 2023d). Hydrogen plays a critical role in the path towards carbon neutrality because by 2050, it is estimated that demand will increase up to 388 Mt, of which (IEA, 2021c) 45% will correspond to demand from the transportation sector, 19% from energy generation sector, 12% to the industrial industry for chemicals, 10% for the iron and steel sector, 1% for the refining sector, and 13% will correspond to other uses.

However, hydrogen production in 2022 came from fossil sources (62% natural gas, 21% coal, and 16% as a byproduct) with a levelized cost of hydrogen (LCOH) in the range

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of 1-3 USD/ kg H₂ and emission intensity (EI) about 9 kg CO₂-eq/kg H₂ (IEA, 2023d). On the other hand, the production of low-emission hydrogen was approximately 0.7% of global demand due to its higher cost, either by options with CCUS with LCOH between 1.5 – 3.6 USD/kg H₂ and EI of 0.7 kg CO₂-eq/kg H₂ (93% capture rate) or by electrolysis using electricity from low emissions with LCOH between 3.4-12 USD/kg H₂ and EI of 0.46 kg CO₂-eq/kg H₂ (IEA, 2023d). However, according to the IEA (2023c), under disruptive decarbonization scenarios and favorable areas, the cost of hydrogen by electrolysis using solar and wind energy could drop to 1.6 USD/kg H₂ and 2.1-2.3 USD/kg H₂, respectively.

In Colombia, the estimated annual demand is 150 kt of hydrogen, and it is mainly consumed in the refinery, with the remainder used for fertilizer production and other minor industrial uses (UPME, 2021b). However, disruption in demand is expected with an increase of 120 kt of hydrogen by 2030 used mainly (94%) for industry, and with a rise in 1850 kt (about 12 times current demand) distributed in transportation. (64%), industry (34%) and electricity generation (2%) (UPME, 2021b).

In Colombia, the current hydrogen production is through SMR (gray hydrogen) in refineries. However, according to Colombia's roadmap for hydrogen, between 1-3 GW of electrolysis capacities and an estimated production of 50 Kt of blue hydrogen are expected by 2030 (UPME, 2021b). Although there is no fixed goal for 2050, it is estimated that demand will be supplied mainly by low-emission hydrogen.

In Colombia, according to MINENERGIA (2022), the LCOH of gray hydrogen using natural gas is 1.9 USD/kg H₂ and could reach 2.9 USD/kg H₂ by 2050; the LCOH of blue hydrogen using natural gas is 2.4 USD/kg H₂ and would be maintained until 2050; and the estimated LCOH for green hydrogen can vary between 2.8 – 6.6 USD/kg H₂ (depending on the study area) and can decrease to a range of 1.5 – 2.4 USD/kg H₂.

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However, other costs must be added to these production costs regarding the storage and transportation (Li et al., 2019; Rivard et al., 2019). Currently, 85% of the hydrogen produced is consumed on-site, while the other 15% is transported, but it is expected that hydrogen must be stored and transported for emerging demands (IEA, 2019c). The most commercial applications (but not the only options) are storage as liquefied and compressed gas (Corporación Ruta N, 2015; Durbin & Malardier-Jugroot, 2013; Rivard et al., 2019).

The problem is the implications in terms of energy costs; about 35% of the energy content of H₂ must be used for the liquefaction process, which is almost three times the energy necessary to compress that same amount of hydrogen at 690 atm (Durbin & Malardier-Jugroot, 2013). Although storage as compressed gas is the most common, the limitations are volume management and the complexity of transporting large volumes over intercontinental distances without connection infrastructure (pipelines) (Van Leeuwen & Jachin Gorre, 2018). On the other hand, the advantage of the liquid state is its ease of transportation through trucks or ships with intercontinental distances that can cover volumes of up to 350 t/d (Ahluwalia et al., 2019; BloombergNEF, 2020).

4.3.4 Carbon capture use and sequestration

Although the different scenarios studied by the IPCC (2022) show that there is no single technology that can achieve the Paris Agreement by itself, the option of Carbon Capture and Sequestration (CCS) is fundamental to complement the technological portfolio since it has a wide possibility of applications, especially in those sectors that are challenging to decarbonize. According to the World Energy Outlook by IEA, 2019d), CCS technologies will have achieved close to a 9% reduction in accumulated emissions by 2050 to comply with the Paris Agreement.

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The IPCC (2005) defined CCS through stages consisting of the separation of CO₂ from industrial and energy sources, including the power and O&G sector; the transportation of this CO₂ to an appropriate location, if applicable; the long-term storage of this CO₂ then it is not in contact with the atmosphere. Recently, a new component has been added that converts this process into carbon capture utilization and sequestration (CCSU), which not only seeks to sequester CO₂ from the atmosphere but also put it to use and valorize the CO₂. (IEA, 2023g; E. Yáñez et al., 2020a). Among the main uses, we find the injection of captured and stored CO₂ as an improved recovery method, also called CCS-EOR (Guo et al., 2020; Yáñez et al., 2022a; Younis et al., 2023). A clear example of this process is the Zhongyuan Oil Field project (China), in which refinery CO₂ is captured - specifically from an FCC unit- and then injected -in the second period of 2015, about 113,800 t CO₂ was injected-, which allowed crude oil production to increase by 33,000 tons of crude oil equivalent per year (T. Zhang et al., 2017).

Regarding the sequestration stage, different technologies allow the capture of CO₂ (IPCC, 2005; Lotz & Brent, 2008): Post-combustion, where the CO₂ is separated from the flue gas stream exiting the combustion process; Pre-combustion, where the fuel first passes through a reactor to produce a stream of CO₂ and H₂, which is then used as fuel; Oxyfuel, where the air is replaced with high purity oxygen so that the combustion products are mainly CO₂.

Regarding transportation, pipelines can be used for large quantities, while CO₂ commitment can also be carried in trains and road tankers, but this is usually not attractive due to its small scale (Lotz & Brent, 2008). However, according to the IEA carbon neutrality scenario, 95% of the captured CO₂ will be stored geologically, and 5% will be used to produce synthetic fuels (IEA, 2021c).

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Yañez et al. (2022) estimated the potential for CO₂ storage and incremental recovery using the CO₂-EOR technique in Colombia through deterministic and stochastic approaches. They found that five oilfields –located primarily in the MMV sedimentary basin- may have great potential for this technique, estimating a potential of oil recovery and CO₂ storage of 690 Mbbl and 203 Mt CO₂, respectively. Likewise, the sources of CO₂ capture in Colombia would be concentrated in the O&G, cement, power generation, and ethanol production industries, with an estimated capture potential of up to 18 Mt CO₂ per year, of which only 5.9 Mt CO₂ could be used. for CO₂-EOR (E. Yañez et al., 2020a). Furthermore, carbon capture and sequestration, along with bioenergy, can play an essential role in the decarbonization of Colombia. (Younis et al., 2021), achieving up to 37-41% of accumulated emissions avoided between 2030 and 2050 in the most disruptive scenario in terms of decarbonization (Younis et al., 2023).

4.3.5 Environmental policies

Carbon pricing is one of the most common mechanisms countries use to materialize their commitment to the Paris Agreement (found in article 6) (IEA, 2023i). The latter consists of penalizing GHG emissions and promoting clean technologies. There are two main types of carbon pricing (The World Bank, 2023a): the first is called the Emissions Trade System (ETS), also known as the cap-and-trade system, and estimates an emissions limit by industries, then they can market surpluses or shortages with other sectors, and stipulate an emissions market based on supply and demand; The second is the carbon tax, in which there is directly a fixed price for each GHG emission emitted. In both cases, the success of these policies will depend on the fixed carbon cost covering the most significant number of

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emissions and sectors and that the price or limit increases over time according to the evolution of the instrument and the economy (i.e., energy crisis inflation, among others) (IEA, 2021c).

Carbon pricing mechanisms have increased their coverage of global emissions from 7% to 23% (around 11.6 Gt CO₂-eq) in the last ten years; currently, 18% of the coverage is due to ETS and the remaining 5% to carbon tax (The World Bank, 2023b). By 2023, 89 jurisdictions had defined carbon pricing mechanisms, 49 at a national level and 40 at a sub-national level (The World Bank, 2024).

Colombia has stipulated carbon pricing by regulating the carbon tax through Article 222 of Law 1819 of 2019, which establishes a price for the emission of GHG through the combustion of fossil fuels (Ley 1819 de 2016, 2016). This figure was 4.96 USD/t CO₂-eq in 2022 (IETA, 2022). Additionally, the Colombian government committed in December 2021, through law 2169 of 2021, also known as the climate action law, to fully implement an ETS by 2030.

Furthermore, to meet the carbon neutrality goal, the IEA (2021b) mentions that other public policies are necessary, including the partial withdrawal of inefficient subsidies for fossil fuels and the incursion of loans or subsidies towards clean technologies. In energy models, these can be interpreted as scenarios in which low-emission technologies have a more favorable cost to compete in the market.

4.4 Methods and data

For this chapter, we started from scenario S1 (BAU) and the RES of the TIMES-O&G model presented in chapter 3 and detailed in appendices A and B. the RES was extended to the disruptive scenario in terms of decarbonization through the detail in Appendix C. It is

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highlighted that the framework of the TIMES-O&G model and its fundamental structure (see sections 3.2.1 and 3.2.2 were not modified).

Error! Reference source not found. compares scenarios S1 and S4, in accordance with the assumptions of energy systems modeling and the National Energy Plan.

Table 5. Comparison between BAU and disruptive scenarios.

Module	Scenario variables	S1	S4
	Scenario of consumption*	Updating	Upgrading
	Final consumption in the energy sector in 2050, PJ	1,905	1,570
Demand side	Final consumption of fossil fuels in 2050, PJ**	1,291 (68%)	919,4 (59%)
	Total Emissions in 2050, Mt CO ₂ -eq***	90	53
	Hydrocarbon reserves scenario	Medium (16,467 PJ)	Low (14,778 PJ)
Supply-side	YTF hydrocarbon resources scenario	Medium (8,767 PJ)	Low (429 PJ)
	New generation plants	Thermal plants without the CCS option	Thermal plants with and without CCS option, and biomass power plant option.
	Economic and technical parameters of power generation	ATB-2021-Conservative Scenario	ATB-2021-Advanced Scenario
Conversion processes	New renewable capacities	Yes (Solar-PV and Land-Based Wind Energy)	
	Production technologies for hydrogen	Grey	Grey, blue, and green sources****
	Blending with biofuels	10%	15%
	LPG scenario*****	Medium (11.51 PJ)	High (21.88 PJ)
	Biorefineries	No	Yes

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Changes in refinery outputs		Yes	
Fuel price	Carbon tax	Current (7 USD/t CO ₂ -eq)	10-20 USD/t CO ₂ -eq and then a 5% increase every year.
	Emissions coverage	According to Law 1819 of 2019	Every fossil fuel, including exports.
	Demand and cost of hydrogen*****	-	According to Colombian's Hydrogen Roadmap
	Crude oil prices in 2050		16,9 MUS\$2019/PJ

*Refers to the selected PEN scenario. There is another scenario called "disruptive," but it was not considered in this study because it includes the penetration of hydrogen and technologies associated with its value chain, which is outside the scope of this study.

**It refers to the final consumption of fossil fuels related to the O&G sector, which is the demand of the TIMES-O&G model.

***It refers to the total emissions from consumption by final users of the energy sector in Colombia, as estimated by the PEN.

****Grey production refers to steam methane reformer (SMR) technology, blue production refers to SMR+CCS, and green production refers to electrolysis technology. (UPME, 2021b)

***** Regarding LPG processing capacities in oilfields, see Annex 2, section 3.8.

*****it refers to the cost of a competitive price for the hydrogen market. See Appendix C.

4.5 Main results

Figure 24 and Figure 25 present the balances (supply and demand) of crude oil and natural gas in scenario S4 compared to S1, in which a decrease in demand for both commodities is observed. In the case of crude oil, it is observed that by 2050 in S4, the demand from refineries has decreased 46% compared to S1, which is due to the decrease in demand for refinery products (diesel, gasoline, and LPG mostly). Regarding natural gas, the decrease is similar to that of crude oil (41%), mainly due to the reduction in consumption of the sectors defined by the PEN. Regarding the import balance of crude oil and natural gas, in both scenarios (S1 and S4), it is seen that imports exceed in the long term (after 2040); however, in scenario S4 it is seen that even for the year 2030, The import of crude oil and natural gas represents a percentage of the supply of 54% and 47% respectively, which is 14% higher (for both crude oil and natural gas) compared to scenario S1.

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Figure 24. Balance of crude oil in S1 and S4 scenarios.

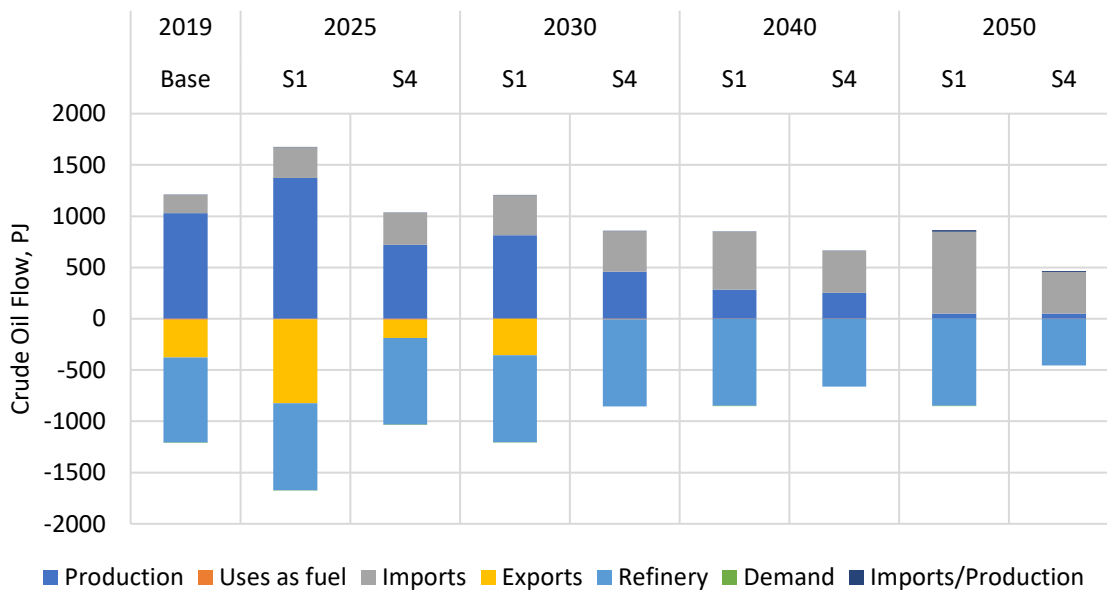


Figure 25. Balance of natural gas in S1 and S4 scenarios.

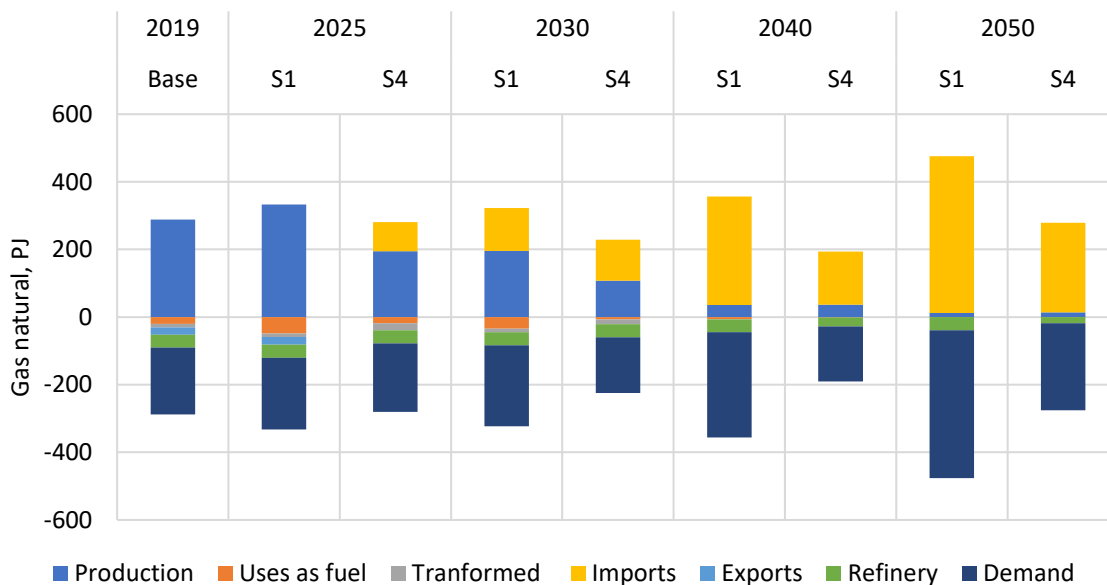
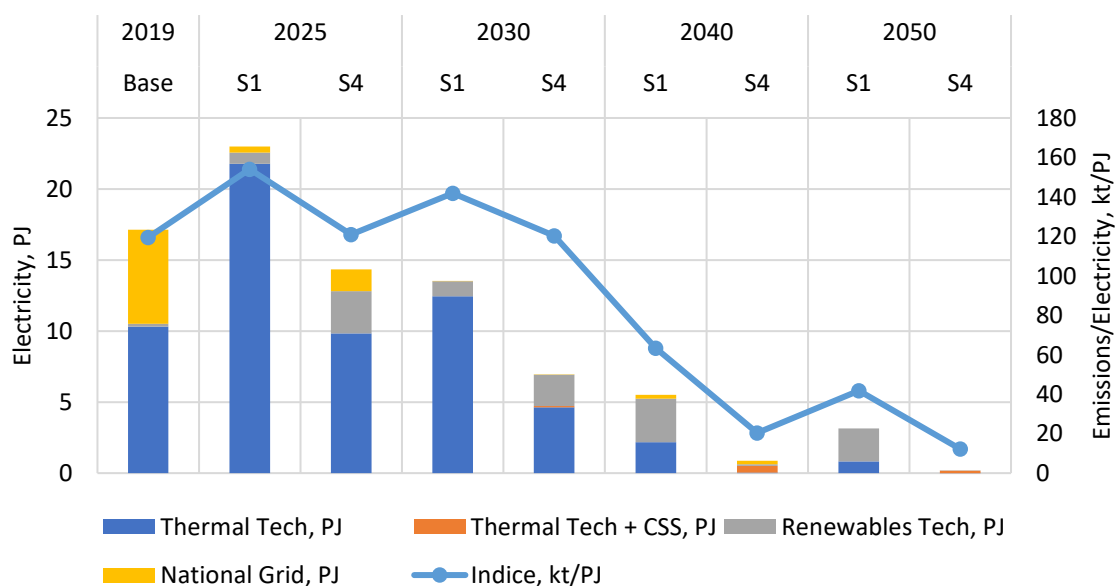


Figure 26 presents the energy matrix of the production and transportation segment of scenarios S1 and S4. It should be noted that S1 uses the moderate cost projection of technologies for electricity generation, while scenario S2 uses the advanced projection (a lower cost for technologies focused on the transition, including natural gas). The above has

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a short-term implication, since in 2025, an increase in hydrocarbon production is observed due to the addition of new resources (YTF) (Figure 24) scenario S1, which implies that new generation capacities must be installed, and to at that time, the most cost-effective thermal technologies compared to the price of the national grid and renewable energies; However, for scenario S4, although an increase in production is not expected, the cost scenario favors the installation of renewable energy capacities (for this moment, solar energy) to shift the purchase of electricity to the national grid. In the medium term, in scenario S1, renewable energies only begin to participate in the generation matrix from 2040, but they do so disruptively so that in that year, the participation of renewables constitutes 58% of the energy matrix. On the other hand, in S4 for 2040 there is no significant production of crude oil - around 5% compared to the base year- (Figure 24). Hence, the energy matrix is not so diverse, however it is highlighted that since 2030 thermal technologies with carbon capture (in this case, only technologies based on natural gas) begin to participate in this energy matrix, and are even the most representative of that matrix for 2040 and 2050.

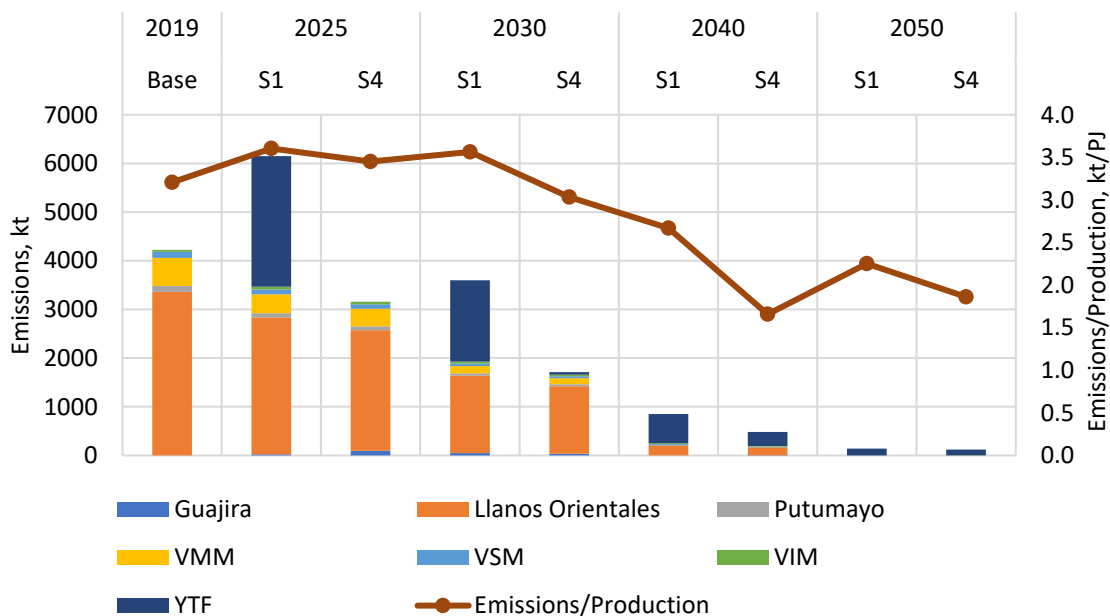
Figure 26. Sources of electricity generated for production in S1 and S4 scenarios.



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Figure 27 presents the emissions from the production and transportation segment. Over the entire time horizon, it can be seen that the IE of scenario S4 is lower than that of scenario S1, especially for the year 2040, when the difference in emissions generated between both scenarios is 43%. Similarly, the reduction in emissions generated per unit of hydrocarbon produced reduces scenarios S1 and S4 between 2050 and the base year by 29% and 42%, respectively. This reduction is mainly leveraged by the diversification of the clean technology energy matrix since, between 2019-2050, the index of emissions generated per unit of electricity generated in these segments decreases between 65% and 89% in the scenarios—S1 and S4 respectively (Figure 26). However, despite the efforts, expanding the portfolio of technologies available is necessary to decarbonize the production and transportation segment, especially if scenarios are considered where resources and reserves are more significant, since emissions will also be higher.

Figure 27. Emissions from the production stage in S1 and S3 scenarios.



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Figure 28 presents the distribution of fuel production in the refineries. The results show the trend of the transition towards cleaner energy sources in the consumption sectors exposed in the PEN, so that, in this S4 scenario, the activity of the refineries begins to decrease in 2040 - and not from 2050 as happens in scenario S3-, and in 2050 the refineries operate at 46% of the maximum capacity observed in scenario S1. The above implies that in scenario S4, not only does the company make a transition from producer and refiner of hydrocarbons to the role of importer, but also, the company limits itself to refining only what is necessary to supply national demand, but under the fuel price and cost scenarios, the activity of importing crude oil to refine it and export fuel is not contemplated. On

Figure 28. Production of fuels in refinery in S1 and S4 scenarios.

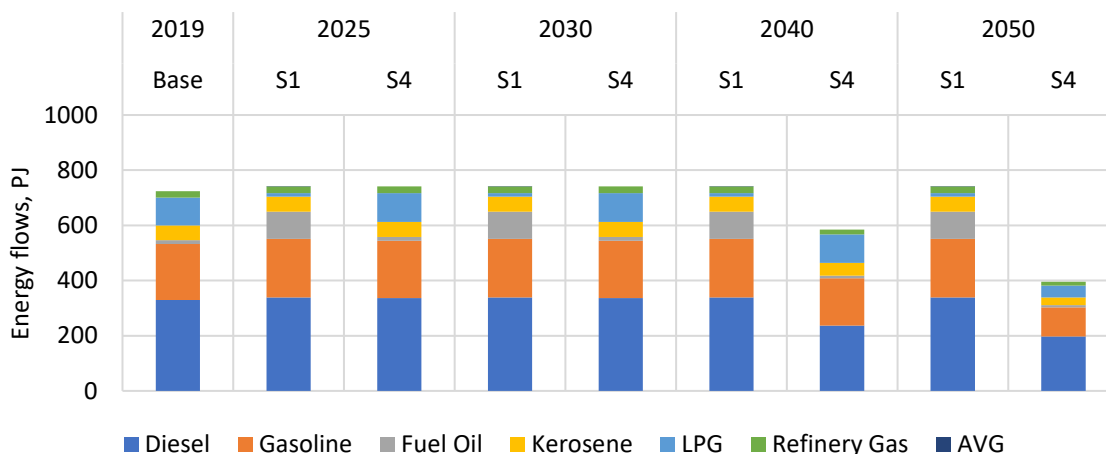


Figure 30 shows the results of scope 3 emissions for both scenarios. While in scenario S1, emissions from consumption sectors increase by 59% between the period 2050 and 2019, S4 emissions remain relatively the same (1% increase). However, the emissions that would be part of the products that are not burned in Colombia but that are an exporter are always lower in scenario S4 compared to scenario S1 over the entire time horizon, which is in line with the decrease in the role of hydrocarbon exporter in scenario S4. These changes in demand lead

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to changes in the distribution of fuels produced in scenario S3 because the production of diesel and LPG is prioritized, which can represent up to 50% and 18%, respectively (in 2050 for diesel and 2040 for LPG), which is greater than in scenario S1, where the maximum participation reached for diesel and LPG are 48% and 2% respectively, which is due to changes in the distribution of fuel national demand.

Figure 29. Emissions from scope 3 in the S1 and S4 scenarios.

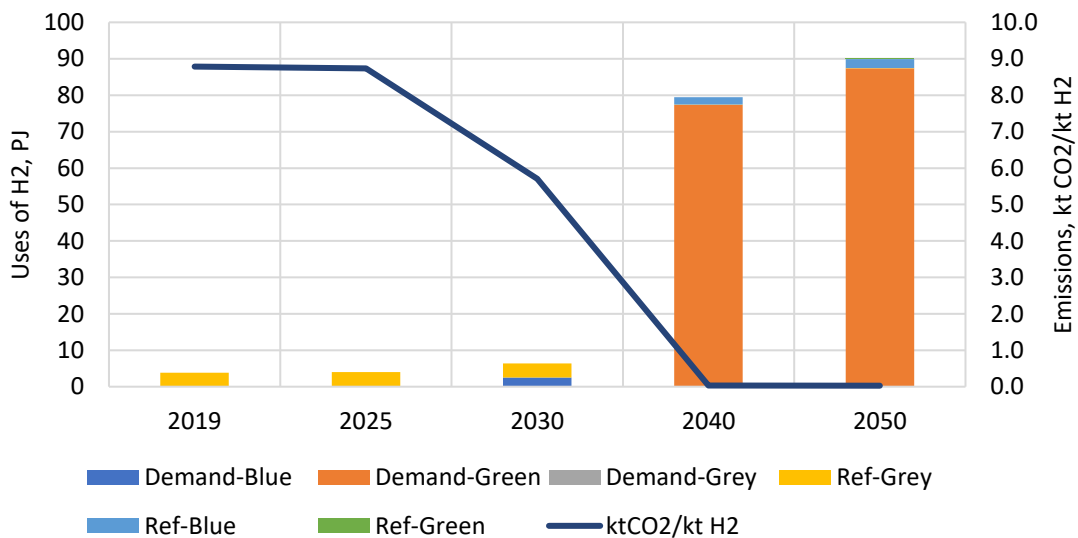


Regarding the inclusion of hydrogen in the value chain of the conceptual company O&G, Figure 30 presents the production of hydrogen by the different sources (gray, blue and green hydrogen represented by SMR, SMR+CCS, and electrolysis technologies, respectively). Before 2030, hydrogen demand comes mainly from refinery requirements, and the model calculates that the only production technology is SMR, with an emission factor of approximately 9 kt CO₂/kt H₂. However, in 2030, the Hydrogen production comes from both SMR and SMR+CCS, but predominated by non-capture technology with 61%, which reduces the emission factor of the hydrogen production segment by 35% (up to 5.7 kt CO₂/kt H₂);

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however, this year hydrogen is not produced to supply national demand. Now, in the long term, in 2040 an investment is made in installing renewable electricity generation and electrolyzer capacities to produce hydrogen. electrolysis means to supply the national demand, while, to supply the refinery demand, only SMR-CCS technology is used; Regarding the contribution to the national demand for hydrogen, the company could contribute up to 100% of the demand in 2040 because in this year a large investment is made to install green hydrogen generation capacities, however, they are not added new capacities in 2050 so that this year only 67% of national demand is provided, so the remainder must be assumed by other third parties.

Figure 30. Uses of hydrogen in S4 scenario.



4.6 Summary of the chapter

In Chapter 3, scenarios S1, S2, and S3 were represented, which are equivalent to the updating (BUA), upgrading, and inflection scenarios to establish the energy reference scenario of the TIMES-O&G model. Although these scenarios include some of the

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technologies available for the sector's decarbonization (see Table 4), they do not include a more robust portfolio, such as scenario S4, which is equivalent to the disruptive scenario in decarbonization.

This chapter presents the review of GHG emissions from the O&G industry and how they can be mitigated in the long term according to different energy system models in the most robust decarbonization scenarios. Then, these decarbonization technologies are identified, and we discuss whether those are represented in the PEN by UPME. Then, we present how they can be integrated into the RES of the TIMES-O&G model, with particular emphasis on carbon capture for electricity generation technologies and hydrogen production.

Finally, the company's strategic fit in the disruptive scenario (S4), which includes robust decarbonization technologies, is compared with the BAU scenario. The results show that it is possible to reduce scope 1 and 2 emissions from the production and transportation segment, leveraged mainly by renewable technologies participating in the company's energy matrix. At the same time, it is also observed that there is a trend to decarbonize hydrogen production both by the company and by Colombian demand.

5. Conclusions

- The TIMES-O&G model was developed to represent the typical activities of an O&G company in the Colombian context. The model defines: 36 oil and natural gas fields, grouped in 6 sedimentary basins, and representing around 78% and 52% of the production of the national oil company and Colombia, respectively; 2 refineries, which represent 100% of the country's refining capacity; self-generation processes using fossil fuels and non-conventional renewable sources.
- The TIMES-O&G model was validated with other projections and models. Then, it satisfactorily represents, from an energy systems model perspective, the typical operations of an O&G company. The proposed new structure for O&G activities opens the door to new uses of the TIMES model for the O&G industry, such as regional analysis according to sedimentary basins, energy generation and consumption for operations, quantification of scope one emissions and 2, the integration of decarbonization technologies for operations.
- The O&G sector's self-sufficiency is uncertain in Colombia: By 2030, in the average hydrocarbon supply scenario (S1), imports of oil and natural gas will correspond to 46% of demand; in the case of the low hydrocarbon supply scenarios (S2 and S3), imports will represent 54% and 49% of total demand for the same date; the trend is accentuated until, in 2050, imports will represent 92% and 100% of demand, respectively.

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- The hydrogen value chain, renewable energies, and CCS were identified as the leading decarbonization technologies for the O&G company, based on the strategic lines of the National Energy Plan of Colombia and insights from scenarios of decarbonization of other global energy models. The above technologies were modeled according to the energy systems modeling approach, extending the reference energy system of the TIMES-O&G model.
- The impact of international regulations in the model was taken into account through carbon rate, changes in the costs of decarbonization technologies through scenario projections, and projections of the cost of fossil fuels using price scenarios. It was found that the changes in the demands of the Colombian demand sectors impact the import and export flows of the company because, in the three scenarios, it was observed that the main challenge that must be faced is fossil fuel self-sufficiency. Furthermore, policies aimed at accelerating clean technologies (such as electricity production through renewable energy and gas generation with capture) through subsidies that reduce costs can accelerate their participation in the energy matrix, as observed in scenario S4.

6. Recommendations

The authors recommend that the modeling of energy systems with a focus on the hydrocarbon value chain can be expanded if:

- The model should be expanded regionally (by sedimentary basins) on the potential for new resources, with greater detail on technical-economic parameters, since adding new resources represented in specific scenarios was done in a single group. Within these analyses, the evaluation of unconventional reservoirs can be included to establish evidence of the implications of their exploitation.

The demand must be computed endogenously since the demand of the TIMES-O&G model was established exogenously. This new approach will strengthen the model by opening up a range of opportunities to delve directly into the energy services rather than the fuels that are used.

The decarbonization technologies represented in the TIMES-O&G model must be deepened and expanded as new technical, economic, and environmental information on the technologies becomes available. Studies that consider other specific decarbonization technologies, such as e-fuels, CO₂ valorization, urea production, and the hydrogen supply chain (not only production but also storage, transportation, and uses), are also suggested.

In the area of energy system modeling, it is recommended to evaluate the same scenario or driver through different models (e.g., TIMES-CO-BBE, TIMES-O&G, GCAM for the Colombian model, among others) so that the differences in the methodological approaches of each model, as well as the differences in the results, can be analyzed.

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Appendix A. Documentation of TIMES-O&G model

This document is part of the article “Assessment of the Colombian Long-term Energy Planning Scenarios for the National Hydrocarbon Value Chain: Insights from the TIMES-O&G Model” and contains the necessary data and assumptions to reproduce the TIMES-O&G.

A.1. Overview of the TIMES-O&G model

From the knowledge of the authors, there’s no TIMES model applied solely to an O&G company; the TIMES-O&G model is the first of its kind. Table A.1 presents the differences and similarities of the model developed about those existing in the literature.

Table A.1. Comparison between existing model TIMES in the Colombian context

	TIMES model⁷	TIMES-CO-9 Model⁸	TIMES-O&G Model
Demand module			
Approach	Energy services and chemicals, among others. Sectors and subsectors could group it.	Energy service only	Fuels by consumer sectors since the company does not offer energy services but fuels to the market.
Demand technologies	Detail in techno-economic parameters for each sector. It could include constraints on demand.	Primary database for future technologies (No efficiency improvement). No user constraints on demand.	There’s no detail on demand technologies since they are beyond the scope of the company’s operations.
Projections	It includes drivers (endogenously) such as economic and populational growth, and elasticity, among others.	Basic demand drivers	Based on the projections of the National Energy Plan of Colombia (exogenously)

⁷ Based on typical features of the TIMES models and their applications at the global, regional, and national scales (IEA-ETSAP, 2022; Loulou & Labriet, 2008).

⁸ Since there is no public documentation of the TIMES-CO model, the feature here described are based on what has been reported in the article “System analysis of the bio-based economy in Colombia: A bottom-up energy system model and scenario analysis” (Younis et al., 2021).

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Conversion module

Power system	Existing technologies (e.g., from conventional renewables and/or fossil fuels) and non-existing technologies (e.g., options with CCS)	Only existing technologies	existing	Power generation is focused solely on the company's self-sufficiency.
Refineries	Conventional refineries with options to expand capacity, flexibility in their outputs, and improvement in efficiency. Also, biorefinery applications.	Modernization of existing capacity (flexibility, utilization, efficiency)	of	Greater detail in refineries to consider different decarbonization routes in alternative scenarios.

Supply module

Primary resources	Usually, it represents all the primary energetics at a certain level of detail according to relevance.	Fossil fuels, biomass, and other renewables.		Fossil fuels that are part of the company's value chain (e.g., coal is not considered)
Other renewables	It could include solar and wind energy, hydropower, biomass, geothermal, and nuclear energy, as well as hydrogen and its supply chain.	No information available		Solar and wind energy focus on the company's value chain. It also includes energy carriers such as hydrogen.
Extraction of primary resources	The extractive process is simplified.	The extractive process is simplified by obtaining the resource in exchange for different costs.		More detail in the extractive process (see section 3)

Emissions and mitigations

Emissions	Scope 1, 2, and 3. Special attention in scope 3.	No information available		Scope 1, 2, and 3. Special attention to Scope 1 and 2.
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Mitigation goals	According to scenarios	No information	available	Subject to national policies. It also can evaluate corporate objectives.
Other features				
Temporal resolution	Annual or time slices	Annual		Annual
Spatial resolution	Some specific cases includes quasi-spatial resolution.	No		Quasi-spatial: it differentiates the production by sedimentary basins.
Variable renewables patterns	According to time slices	One region	hydrological	Specific regions for wind and solar energy.

The period of analysis is 2019-2050 (see Table A.2), with 2019 selected as the base year due the extensive availability of data that allows the validation of the model, while 2050 is the final year to be aligned with pricing and demand projections, and mitigation objectives. The resolution of time slices remains at an annual level considering the following assumptions: the activity of the process related to the O&G is usually reported monthly. However there are no significant variations from month to month -e.g., the coefficient of variation for oil and gas production and refinery loading in 2019 is 1, 4 and 6% respectively (ANH, 2021b; UPME, 2021a)-; Since the activity of the processes is annual, the energy/electricity requirement for these will also be annual. Therefore the self-generation processes -including those from renewable sources such as solar and wind energy- were modeled averaging their technical parameters (see section 3.9).

Besides, the units for activity, capacity, and commodity of the model are petajoules (PJ) and petajoules per year (PJ_a). According to the base year and energy units, millions of dollars in 2019 were selected as the currency of the whole model for economic data. The

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discount rate used in this study is based on previous studies focused on ECOPETROL S.A (E. Yáñez et al., 2018, 2020b; É. Yáñez et al., 2021, 2022), a mixed economy company of a commercial nature, integrated into the oil and gas sector in Colombia (ECOPETROL, 2019b), and that is taken as a reference for the construction of this model but without being limited solely and exclusively to this company -e.g., ECOPETROL S.A. does not have a stake in the transportation of natural gas, but the modeled company does -. Finally, interpolation and forward extrapolation will be allowed to calculate projections and technical-economic parameters of entry to the model.

Table A.2. General options for the TIMES-O&G model.

Options	Specification
Base year	2019
Time horizon	2019 - 2050
Time slices	Annual
Energy Unit	PJ
Activity Unit	PJa
Currency	MUSD-2019
Discount Rate	12%
Control of data interpolation	Interpolation and forward extrapolation

A.2. Description of the model

A.2.1 Simplified RES of the model

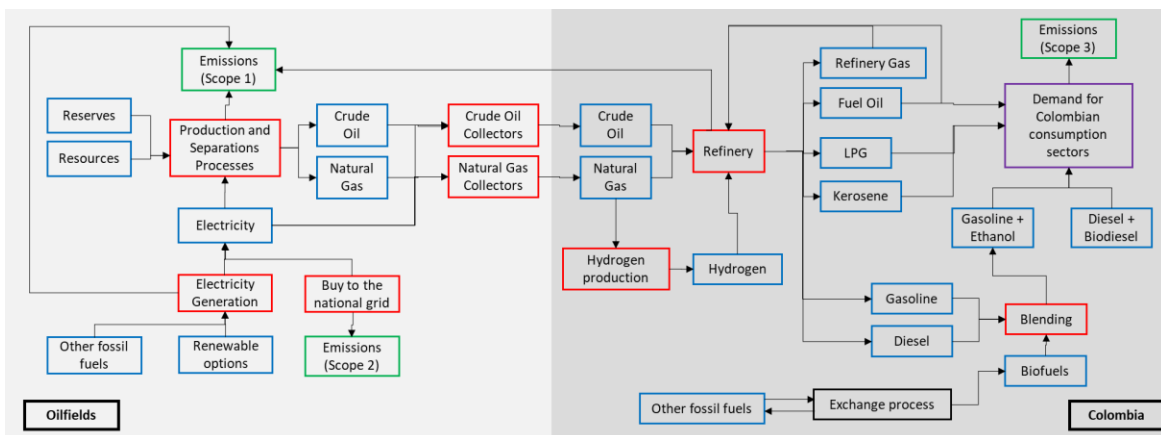
The TIMES-UIS model seeks to explicitly represent the main processes of the O&G value chain, especially those with a high emission intensity and that have representative decarbonization routes. The stages of production, refining, and transport of hydrocarbons are modeled as shown in Figure A.1; although the transportation processes were simplified by

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the following reason: it is estimated that the specific energy consumption and specific GHG emissions of transport stage only represent only 3.58% and 3.74% of the O&G value chain in Colombian context respectively (E. Yáñez et al., 2018), and fact ECOPETROL's emissions in 2019 -year base of this study- were divided as follows: 53% refining, 45% production, and 2% transportation (ECOPETROL, 2019b); the decarbonization options for this stage are focused on changing current technologies to more efficient (E. Yáñez et al., 2018), which implies representing the hydrocarbon transport system in Colombia, which is an extensive task in data collection due to the wide geographical distribution.

The fossil fuel distribution towards the end users and the subsequent use in energy services was not modeled because this activity does not directly concern the company O&G in the Colombian context, and other retail companies are responsible for the final distribution of fossil fuels. Consequently, the value chain modeled ends in the delivery of fossil fuels to the consumption sector indifferently what its subsequent uses will be.

Figure A.1 Simplified RES of TIMES-O&G model



A.2.2 List of fuels

The selection of commodities modeled -specified in the Table A.3- was based on the following:

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- The commodity must be part of the O&G value chain; for example, coal was not considered.
- In the model, electricity is consumed by processes in the O&G value chain, and it is assumed that the company only generates the required electricity, that is, there is no purpose of supplying the national electricity demand.
- The commodity's characterization —heating value and emission factor—was based on the Colombian context; for this reason, the definitions of the UPME (*Unidad de Planeación Minera Energética*) were used.
- Although there is only one available characterization for crude oil, it was divided into three commodities according to the API classification and assumptions made by UPME: light oil (lower than 18 °API), medium (between 18 and 32 °API), heavy oil (greater than 32°). This allows distinguishing the composition of the supply and the input from the refineries and to know what type of crude oil is imported and exported.

Table A.3. List of fuels in the TIMES-O&G

Commodity	Commodity Name	Exact Reference for UPME	Original Unit	Heat	Emission Factor (kt CO ₂ -eq/PJ)
				Value (PJ/UO)	
Natural Gas	GAS	Yes: <i>Gas Natural</i>	MPC	0,001	55,5
Light Oil	LOIL				
Medium Oil	MOIL	Yes: <i>Petróleo</i>	Mbl	6,087	77,8
Heavy Oil	HOIL				
Gasoline	GSL	Yes: <i>Gasolina Motor</i>	Mbl	5,331	69,2
Diesel	DSL	Yes: <i>Diesel</i>	Mbl	5,671	75,2
Kerosene	KER	Yes: <i>Keroseno y Jet Fuel</i>	Mbl	4,712	87,7
LPG	LPG	Yes: <i>Gas licuado del Petróleo</i>	Mbl	4,056	47,3
Fuel Oil	HFO	Yes: <i>Fuel Oil</i>	Mbl	5,461	78,3

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Avgas	AVG	Yes: <i>avigas</i>	Mbl	4,762	56,3
Refinery Gas	RFG	Yes: <i>Gas de Refinería</i>	MPC	0,001	40,8
Ethanol	BDSL	Yes: <i>Alcohol Carburante</i>	Mbl	5,193	84,8
Biodiesel	ETH	Yes: <i>Biodiesel</i>	Mbl	5,634	54,8
Electricity	ELC	Yes: <i>Electricity - 2019</i>	Gwh	-	49,02 (UPME, 2016)

Note: The emission factor for the national grid (electricity) presented is the average calculated for 2009-2021.

A.2.3 Demand scenarios

The demand module was established exogenously based on the PEN (*Plan Energético Nacional*), which projects the demand for commodities from 2019-2050 under four scenarios (UPME, 2020c). The results of the PEN were obtained through the LEAP model built for Colombia; this is a bottom-up simulation model, which allows the analysis of energy policies and evaluation of climate change mitigation. However, this model does not identify the lowest cost systems or optimize the participation of energy sources based on price and variables (UPME, 2020b). This study assumes assumptions made by the PEN for each scenario about demand and final use; some of those are shown below. Regarding the supply and conversion, the TIMES-O&G model uses the assumptions of the PEN as a starting point but expands and improves the detail of these modules as presented in sections 3 and 4.

In addition, it should be noted that some processes of the O&G company require fossil fuels, for example, natural gas for refineries, and this is an additional requirement of the commodity stipulated by the consumer sectors.

Table A.4. Demand assumptions of scenarios proposed by PEN.

	Updating	Upgrading	Inflection	Disruption
Brief description	Aligned with current trends	Gasification as a step toward the decarbonization	At the start of the economy, electrification	Innovation to align the sector to carbon neutrality

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Economics	GPD economic growth in 3.1% (base)		GPD economic growth is 3.5% (Optimistic)	
Energy⁹	Balance Energético Colombiano - BECO, 2010-2019			
Efficiency in sectors¹⁰	Best Available Technology - BAT Colombia 2050	BAT International 2050	BAT International 2040	BAT International 2030
Residential	Reduction of firewood consumption by 30% by 2030 and by 60% by 2050	Reduction of firewood consumption by 50% by 2030 and by 80% by 2050. Substitution by LPG	Reduction of firewood consumption by 80% by 2030 and by 100% by 2050. Substitution by LPG	
Industry	Industrialization with natural gas - replacing coal- from 30% to 40%.	Industrialization with natural gas -replacing coal- from 30% to 45%.	Electrification of direct heat up to 15%	Replacing fossils with green hydrogen in processes thermal (industry) 5% - 10% demand
	The historical fleet for 2019 from Registro Unico Nacional de Transporte - RUNT is projected to have 29 million vehicles in 2050.			
	Gradual adoption of BAT			
Transport	Light transport: 11% electric in 2030 and 23% in 2050.	Light transport: 40% electric, 15% low emissions (natural gas and LPG).	Light transport: 60% electric, 20% low emissions, and the remaining will be other clean fuels in 2050	Light transport: 80% of sales will be electric vehicles and 20% hydrogen vehicles in 2050.
	Greater participation of LNG and LPG in transporting heavy loads: 30% of the trucks to LNG and	Greater participation of LNG in the transport of cargo - tractor truck- (50%), and 50% sales of	Greater participation of LNG in the transport of cargo -tractor truck- (50%), and 50% sales of compressed natural gas trucks and 20% sales of electric trucks	

⁹ Refers to the energy balance: production, transformation, and final consumption.

¹⁰ Regarding to the consumer sectors: industrial, residential, and tertiary.

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between 7.000 and 8.000 trucks to LPG.	compressed natural gas trucks		
Mass transportation system operating with clean fuels by 2050: 20% electric, 50% low emissions, and 30% natural gas	Mass transportation system operating with clean fuels by 2050: 30% electric, 30% low emissions, and 40% natural gas		100% electric bus fleet by 2050.
30% of the motorbikes will be electric in 2050	40% of the motorbikes will be electric in 2050	50% of the motorbikes will be electric in 2050	By 2050, 70% of motorbikes will be electric and 10% fueled by hydrogen
LPG will be used in national navigation in 9% by 2050.			
Increase in national air transport -between 11% and 14% of the total consumption of the sector-			
-	Three electric rail mass rapid transit (metro)	Six electric rail mass rapid transit (metro)	

For each scenario, five consumption sectors are defined -agriculture, construction, and mining; tertiary; residential; industrial; and transportation-and for each of these, the demand for commodities - hydrogen, charcoal, coke, avgas, waste, crude oil, fuel oil, LPG, firewood, bagasse, mineral coal, kerosene-jet, gas natural, electricity, gasoline, diesel- is presented. However only commodities related to the O&G company was considered (as established in section 2.3). Presents the demand for the reference scenario, which is the updated scenario in the PEN; the demand data for the other three scenarios can be consulted on the UPME website and is processed using the assumptions above. It should be noted that

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The company must supply the Colombian demand of these consumer sectors at the lowest possible cost (optimization problem of TIMES models). Since the electricity demand was not considered, when the use of fossil fuels is replaced by electricity, it will be understood that the company's obligation decreases. Therefore, the comparison between scenarios with different demands must be understood as a relationship between the cost of the system and the energy demand.

A.2.4 Price of fuels

When the company's national demand for commodities is satisfied, the surplus may be exported abroad, lowering the cost of the company's O&G system. Aversely, the importation process means an additional fee for the company. It is assumed that there is a market that will buy and sell commodities according to an international price. This model takes the price projection of the Annual Energy Outlook 2020 developed by the EIA (U.S. EIA, 2019), which has the same base year 2019 as this model. However, there are no projections for biodiesel and avgas, so it was assumed that the behavior over time of these two commodities is equal to that of diesel and jet kerosene, respectively, based on the fact that this has happened in recent years, as shown in the Figure A.2. In addition, electricity refers to the purchase and sale of the national grid. Therefore, the Colombian price will be used and will be projected according to the AEO-2020 trend.

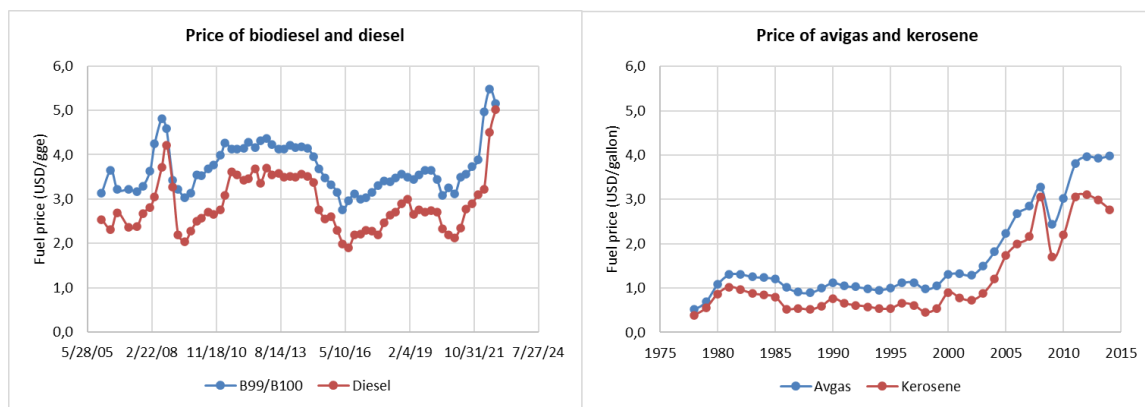
Table A.6. Source of projection of prices for commodities in TIMES-O&G

Commodity in TIMES-O&G	Reference in AEO-2020	User
Natural Gas	Natural Gas	Average price for all users
Fuel Oil	Residual Fuel Oil	Average price for all users
WTI Crude Oil	WTI Crude Oil	Crude oil prices
Kerosene-Jet	Jet Fuel	Average price for all users

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Ethanol	Ethanol	Wholesale price in transportation
LPG	Propane	Average price for all users
Diesel	Distillate Fuel Oil	Average price for all users
Gasoline	Motor Gasoline	Average price for all users
Electricity	Electricity	Average price for all users
Biodiesel	No	-
Avgas	No	-

Figure A.2 Evolution of biodiesel, diesel, avigas, and kerosene prices.



Note: Comparison of biodiesel and diesel historical prices based on information from Alternative Fuels Data Center in the US (Alternative Fuels Data Center, n.d.) (left). Comparison between avigas and kerosene historical prices based on information from IEA (EIA, n.d.-a, n.d.-b); data between 2015 and 2020 were not plotted because there is no information available for the avigas.

Even though the AEO-2020 has ten scenarios -each one with the respective projections-the TIMES-O&G model will use the reference scenario of the AEO-2019, as shown in Table A.7. The prices presented below refer to export prices. In contrast, for importation the same rule used in the TIMES-CO-BBE model will be assumed (Younis et al., 2021): the import cost is 30% additional to the export cost for natural gas, while for other fuels it is 23%¹¹. These values are consistent with those adopted in the LEAP model, which stipulates an additional 20% in import costs (Das et al., 2020).

¹¹ This prevents import prices from being lower than export prices.

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Table A.7. Fuel prices in the reference scenario of TIMES-O&G

Reference escenarios AEO-2020 (MUSD2019/PJ)							
	2019	2025	2030	2035	2040	2045	2050
Natural Gas	4,8	4,9	5,4	5,4	5,5	5,5	5,7
Fuel Oil	9,2	9,4	10,8	12,0	13,4	14,3	15,1
WTI Crude Oil	9,4	10,8	11,9	13,3	14,4	15,6	16,9
Kerosene-Jet	13,9	14,5	15,8	17,2	18,2	19,6	20,7
Ethanol	15,5	16,8	19,6	19,7	20,3	21,4	24,2
LPG	17,6	19,9	22,0	22,9	24,4	25,9	27,4
Diesel	20,9	20,6	21,9	23,1	23,9	25,1	25,9
Gasoline	21,0	20,7	22,2	23,6	24,6	25,9	27,2
Biodiesel	27,0	26,7	28,3	29,8	30,9	32,4	33,4
Electricity	34,7	35,2	35,5	35,8	36,0	36,4	36,8

In addition, the model distinguishes between light, medium, and heavy oil, and so do the prices. To establish the prices of each of these, the assumption made by UPME in the liquid fuel supply plan was considered: for light crude the value of WTI is assumed, for medium WTI crude - 0.74 MUSD/PJ (4.5 USD/bl), and for heavy crude - 1.48 MUSD/PJ (9 USD/bl) (UPME, 2021c).

A.2.5 Scope of emissions

This study used the emission factors approach to estimate the emissions related to the O&G company (IPCC, 2006). The basic equation is therefore:

$$Emissions = Activity Data * Emissions Factors$$

Where activity data refers to the quantified measure of an activity that releases emissions such as: fuel consumption, gas flaring, among others. The emissions factors are expressed in equivalent carbon dioxide per activity data ($CO_2\text{-eq}$) and were calculated at level tiers 2 since we use the emissions factors listed by UPME (see Table A.3).

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The model classifies the emissions into three scopes¹² (as observed in the Figure A.1), according to the description for an O&G company by IRENA (Asmelash & Gorini, 2021):

- Scope 1: refers to the emissions produced during direct activities, in this case the stages of production, transportation and refining. It includes: the combustion of fossil fuels for self-generation and self-consumption (e.g., gas natural consumption in refineries); venting and flaring in direct process¹³.
- Scope 2: when the company cannot self-supply the electricity necessary for its processes, then it must make a purchase from the national grid, and this will imply emissions according to the emission factor established by UPME (see Table A.3). For the base year, the net effective capacity of the national grid is mainly made up of renewable energies (68%)¹⁴, and Colombia has established as objectives the diversification of the energy matrix to achieve its energy vision in 2050 (UPME, 2020b), for which a reduction in the intensity of emissions of the electrical system is expected. The model assumes the results proposed by the TIMES-CO-BBE model that evaluates the energy matrix of Colombia under different scenarios, and which establishes the reduction of the intensity factor of the national grid up to 5.83 kt CO₂-eq/PJ (0.021 t CO₂/MWh) by 2050 (Younis et al., 2021).
- Scope 3: refers to the use of fossil fuels related to O&G industry for end users -either if it is used by the Colombian consumer sectors or if the fuel is exported- using

¹²In this way, the model can evaluate specific mitigation goals for each scope. ECOPETROL committed to reaching zero net carbon emissions in 2050 (scope 1 and 2) and reduce CO₂-eq emissions by 25% compared to 2019 (scope 1 and 2). Additionally, it has a 50% goal of its emissions by 2050 (Scopes 1, 2 and 3) (ECOPETROL, 2022).

¹³ While combustion activities are modeled using fuel emission factors, venting and flaring activities will be taken from the specific GHG emissions reported for an O&G case study in Colombia (E. Yáñez et al., 2018).

¹⁴ According to XM report: in 2019 the net effective capacity of the electric system in Colombia is 17.462 MW distributed as follows: hydropower (68.1%), natural gas (11.2%), coal (9.3%), liquid fuels (8.74%), self-generation (0.6%), wind (0.1%), CHP (0.85%), solar (0.05%), and other thermal generation options (1.06%). In addition, for the same year, the participation of renewable energies in the generation of electricity in Colombia reached about 78% (XM, 2019).

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emission factors for fuels listed in Table A.3. The fuel emission factor will be the same regardless of the consumption sector used since the information for each sector is not available for the Colombian context.

A.3. Supply module (including transport)

A.3.1 RES of the supply module

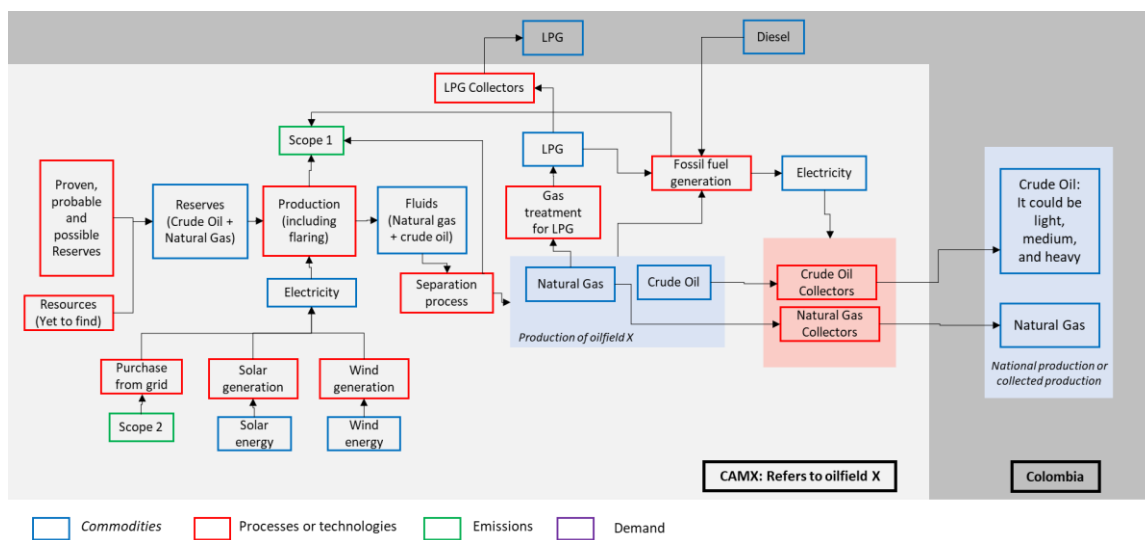
The TIMES-O&G seeks to model the particularities of hydrocarbon production in the Colombian context, therefore oilfield production was modeled, and then added to national production for later use, as shown in Figure A.3. In this way, the particularities of each oilfield or region can be capture. In general, the supply of hydrocarbons can have the following characteristics:

- According to the scenario, reserves and resources may or may not be considered.
- The fluids (reserves of hydrocarbons) are produced through a process that includes the flaring of natural gas by default as a percentage of the total produced. From this process, natural gas and crude oil are obtained according to the gas-oil rate (also known as GOR) of each oilfield.
- The previous process requires electricity, which can be obtained by purchasing from national grid or self-generated by renewable energies and/or fossil fuels, considering: generation by natural gas, crude oil, diesel, LPG, and solar and wind energy depend on the availability of the oilfield, whereas it is assumed that diesel and LPG can be transported to the oilfields.

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- The crude oil and natural gas produced from an oilfield cannot be used by a refinery, to meet demand or for exportation. For the above purposes, hydrocarbons must be collected¹⁵ in a national production or collected production.
- The natural gas can go to natural gas treatment centers for LPG generation according to the facilities in each oilfield. It is assumed that natural gas is transformed into LPG in a certain proportion, while the remainder is sent to natural gas collectors.

Figure A.3. RES of hydrocarbon supply in TIMES-O&G



A.3.2 Selection of oilfields

The choice of oil and gas fields included in this model considered the following:

- The ANH production report for the base year was taken as the database (ANH, 2021b).
- Represents at least 80% of the production of the reference company, that is the ECOPETROL group (includes ECOPETROL S.A., Hocol, and Equion Energy).

¹⁵ Note that natural gas and oil are not collected by a single process, rather, each fluid has its own collector. This allows to capture situations in which small volumes of a fluid are produced and that do not have transport facilities.

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- Does not include oilfields in which ECOPETROL has a stake but does not directly operate the oilfield.
- The selected fields must cover the department in which the ECOPETROL group gas the greatest incidence¹⁶.
- Information must be available for modeling.

Table A.8 presents the thirty-five oilfields that meet the above criteria. For the characterization of the API gravity, it was considered: when an oilfield had a range of API gravity, the average of the maximum and minimum of the range was taken; for fiscalization purposes the ANH distinguishes oilfields by location and contract, even if these oilfields have very similar characteristics, then when no API information was found for a specific oilfield, the value for grouped oilfield was considered, for example, the model assumes that Apiay and Apiay Este have the same API gravity.

Table A.8. Most prolific fields of the reference company

Oilfield (ANH, 2021b)	Grouped Oilfields	Sedimentary Basin(UPME, 2018a)	Location (city or town) (ANH, 2021b)	Department (ANH, 2021b)	API Gravity
					8 (Chaustre Ruiz et al., 2014)
Akacias	Akacias	LO	Acacias/Guamal	Meta	
Apiay					13,5
Apiay Este	Apiay	LO	Villavicencio	Meta	(Jaimes et al., 2014)
Ballena	Ballena	GU	Manaure	Guajira	Only Gas
Casabe					21
Casabe Sur	Casabe	VMM	Yondó	Antioquia	(Gheneim)

¹⁶ Although the ECOPETRO group has operation in other countries (Brazil and the United States), these were not included since the model only covers the Colombian context.

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					et al., 2017)
Castilla					13,7
Castilla Este	Castilla	LO	Acacias/Castilla Nueva	Meta	(Mercado et al., 2009)
Castilla Norte					
Chichimene					13,5
Chichimene SW	Chichimene	LO	Acacias/Guamal	Meta	(Guarin et al., 2010)
Chuchupa	Chuchupa	GU	Manaure	Guajira	Only Gas
Cupiagua					48
Cupiagua Liria					(Alfredo & Ovejero, 2017)
Cupiagua Sur	Cupiagua	LO	Aguazul	Casanare	
Cusiana					52 (E. Suarez, 2019)
Cusiana Norte	Cusiana	LO	Tauramena	Casanare	
Dina Cretáceos					
Dina Norte	Dina	VSM	Aipe	Huila	23 (Izadi et al., 2020)
Dina Terciarios					
Floreña					45,5
Floreña Mirador	Floreña	LO	Yopal	Casanare	(Gomez & Rueda, 2014)
Gibraltar	Gibraltar	CO	Toledo	Norte de Santander	Only Gas
Infantas					22,5
La Cira	La Cira	VMM	Barrancabermeja	Santander	(Calvin et al., 2020)

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Orito	Orito	PU	Orito	Putumayo	35 (Posada et al., 2001)
Pauto Sur					46
Pauto Sur Recetor	Pauto	LO	Yopal	Casanare	(Gomez & Rueda, 2014)
Rubiales	Rubiales	LO	Puerto Gaitán	Meta	12,85 (Anaya et al., 2012)
San Francisco	San Francisco	VSM	Neiva/Palermo	Huila	25,5 (A. Suarez et al., 2010)
Tello	Tello	VSM	Neiva/Palermo	Huila	21 (Duarte Prada, 2010)
Yarigui-Cantagallo	Yarigui-Cantagallo	VMM	Puerto Wilches	Bolívar	21 (Maya et al., 2015)
Arjona	Arjona	VIM	Astrea	Cesar	Only Gas
Bonga	Bonga	VIM	Ovejas	Sucre	Only Gas
Mamey	Mamey	VIM	Ovejas	Sucre	Only Gas

LLO: Llanos Orientales; GU: Guajira; VSM: Valle Superior del Magdalena; VMM: Valle Medio del Magdalena; VIM: Valle Inferior del Magdalena; PU: Putumayo; CO: Cordillera Oriental.

However, to simplify the modeling task, the previously selected oilfields were grouped into sedimentary basins and type of fluid produced (see section 2.2) and each one of them was represented as show in Table A.9. Since the *Llanos Orientales* basin is the most prolific in terms of oil and natural gas production, a distinction was made between light oil and heavy oil. In addition, since there is only one oilfield in the *Cordillera Oriental* basin

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(Gibraltar oilfield), then it was added to the Llanos Orientales that produce light oil (CAM2) due to its location and produced fluid (only natural gas).

Table A.9. Sedimentary basin modelled in the TIMES-O&G.

Oilfield in TIMES-O&G	Basin	Type Fluid	Oilfields
CAM1	GU	Only natural gas	Chuchupa, Ballena
CAM2	LO	Natural gas and light oil	Cupiagua, Cupiagua Liria, Cupiagua Sur, Cusiana, Cusiana Norte, Pauto Sur, Pauto Sur Recetor, Floreña, Floreña Mirador, Gibraltar.
CAM3	LO	Natural gas and heavy oil	Rubiales, Castilla, Castilla Este, Castilla Norte, Chichimene SW, Chichimene, Akacias, Apiay, Apiay Este.
CAM4	PU	Natural gas and light oil	Orito
CAM5	VMM	Natural Gas and medium oil	Casabe, Casabe Sur, Yarigui-Cantagallo, La Cira, Infantas
CAM6	VSM	Natural Gas and medium oil	Dina Cretáceos, Dina Norte, Dina Terciarios, San Francisco, Tello
CAM7	VIM	Only natural gas	Arjona, Bonga, Mamey

Note: The Guajira sedimentary basin (Chuchupa and Ballena fields) were included as of 2020, since it was not until this year that the fields were operated by one of ECP's subsidiaries (HOCOL, 2020). Other fields for the Putumayo sedimentary basin were not included because the necessary information to model it was not found (type of crude oil, reserves, decline curve).

A.3.3 Overview of oilfields

Each selected field must have information on at least production and reserves to be modeled. Table A.10 is the result of the historical oil and natural gas data based on the ANH reports and following the lumping presented in the Table A.9. Each oilfield produces both oil and natural gas at the same time, which are related in the model as the amount of natural gas produced with respect to the total amount of fluids produced (G/Pe), assuming that this relationship remains constant over time. However, there are fields that produce approximately only natural gas -e.g., CAM1 which includes offshore dry gas fields and

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CAM7- or crude oil -CAM3 which has a low G/Pe ratio because they are heavy oilfields without associated gas-.

Table A.10 also presents a balance of the uses of natural gas that serves as a reference for modeling. It differs between fiscalized gas and commercialized gas, since the first represents all the gas that is produced, regardless of its future use -e.g., flaring, self-consumption, transformation into other products-, and the second refers only to the gas that is transported to meet national demand, export, and cargo to refineries. This study considered the same balance of the ANH except for the natural gas that is reinjected, a process that was not represented.

Table A.10. Production data for year base of the sedimentary basin modelled (ANH, 2021a).

	Pe	O	G	G/Pe	G _{COM} M	G _{CONS}	G _{FLA}	G _{PLAN} T	G _{TRAN} S	G _{PIPE}
	PJa (kbe/d)	PJa (kb/d)	PJa (MPC/d)	%	PJa (MPC/d)	PJa (MPC/d)	PJa (MPC/d)	PJa (MPC/d)	PJa (MPC/d)	PJa (MPC/d)
CAM 1	68,6 (30,9)	0 (0)	68,6 (186)	100%	66 (179,1)	2,5 (6,6)	0,1 (0,3)	5,6 (15,2)	0 (0)	60,4 (163,9)
CAM 2	376,8 (169,5)	107,6 (48,4)	269,2 (730,2)	71%	221,5 (600,9)	28,8 (78,2)	3,3 (8,9)	82,7 (224,5)	15,5 (42,2)	154,3 (418,7)
CAM 3	726,7 (326,9)	724,7 (326)	2,1 (5,6)	0%	0,2 (0,6)	0,3 (0,9)	1,3 (3,5)	0,4 (1,2)	0,2 (0,5)	0 (0)
CAM 4	5,6 (2,5)	4,4 (2)	1,3 (3,5)	23%	0 (0)	0 (0)	1,3 (3,5)	0 (0)	0 (0)	0 (0)
CAM 5	165,4 (74,4)	160,6 (72,3)	4,8 (13)	3%	2,3 (6,2)	1,8 (4,8)	0,8 (2,1)	1,4 (3,7)	0 (0)	0,9 (2,4)
CAM 6	29,9 (13,4)	28,4 (12,8)	1,5 (4)	5%	0,6 (1,7)	0,2 (0,6)	0,2 (0,7)	1 (2,8)	0,4 (1,1)	0 (0)
CAM 7	13,8 (6,2)	0,1 (0)	13,7 (37,2)	99%	13,5 (36,5)	0 (0,1)	0,2 (0,7)	0 (0)	0 (0)	13,5 (36,5)
Total	1386,8 (623,9)	1025,7 (461,5)	361,1 (979,5)		304,2 (825,1)	33,6 (91,1)	7,2 (19,5)	91,2 (247,4)	16,1 (43,8)	229,1 (621,5)

Note: Pe is equivalent production (gas + crude oil); O is fiscalized oil production; G is natural gas production (fiscalized minus reinjected gas); G/Pe is the relation between gas produced and mixture produced in terms of energy; Gcom is the commercial natural gas (Gpipe+Gplant-Gtrans); Gcons is the natural gas used in the oilfield for self-consumption; Gfla is the natural gas that is flared; Gplant is the natural gas that goes to processing plants; Gtrans is the natural gas that is

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transformed into other products (mainly LPG) in the processing plants; Gpipe is the natural gas that goes directly to gas pipeline.

Thus, the TIMES-O&G model represented 79.5% of ECOPETROL's equivalent production and 56.9% of national production (see Table A.11). Regarding crude oil, the model represents 75.4% and 52.1% of the production of ECOPETROL and Colombia respectively, which is enough to supply the load to refineries in the base year (stipulated in 830 PJ). On the other hand, TIMES-O&G captures 93.7% and 76.4% of the commercial production of ECOPETROL and Colombia respectively, enough to meet the national demand for natural gas in 2019 (stipulated in 295 PJ).

Table A.11. Production comparison between Colombia, ECOPETROL, and TIMES-O&G (ANH, 2021c).

	Colombia	ECOPETROL	TIMES-O&G
Oil production, PJa (kb/d)	1.969 (886)	1.362 (613)	1.027 (462)
Gas production, PJa (MPC/d)	472 (1279)	385 (1044)	361 (980)
Equivalent production, PJa (kbe/d)	2.441 (1098)	1747 (786)	1388 (624)

The proven reserve data was obtained from the GlobalData database (Global Data, n.d.; Offshore Technology, n.d.-b) for the 35 selected fields and the grouping of sedimentary basins was followed and are listed in Table A.12. However, the available reserve data is expressed as equivalent units (crude oil plus natural gas), then to know how many are of each fluid, the previously calculated G/Pe ratio was maintained (see Table A.10). Additionally, the relationship between reserves and current production for each field was presented.

Table A.12. Reserves data for year base of the sedimentary basin modelled (Global Data, n.d.; Offshore Technology, n.d.-b).

Re (Global Data, n.d.)	Re/(O+ G)	G/Pe	Ro	Ro/O	Rg	Rg/ G
PJa (Mboe)	Years	%	Pja (Mbo)	Years	Pja (Mboe)	Years

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CAM1	267 (44)	3,9	-	0 (0)	-	267 (264)	3,9
CAM2	2.159 (355)	5,7	71%	617 (101)	5,7	1.543 (1.527)	5,7
CAM3	6.497 (1.067)	8,9	0%	6.478 (1.064)	8,9	18 (18)	8,9
CAM4	45 (7)	7,9	23%	35 (6)	7,9	10 (10)	7,9
CAM5	1.059 (174)	6,4	3%	1.028 (169)	6,4	31 (30)	6,4
CAM6	283 (47)	9,5	5%	269 (44)	9,5	14 (14)	9,5
CAM7	158 (26)	11,4	99%	1 (0)	11,4	157 (155)	11,4

Note: Re is equivalent proven reserves (crude oil + natural gas that is commercially available); Ro is proven crude oil reserves; Rg is proven natural gas reserves.

The proven reserves of the selected fields represent 90.8% and 73.2% of the reserves of ECOPETROL and Colombia, respectively. However, there is a difference between the ratio of natural gas reserves to the total reserves of the model (19.48%) with ECOPETROL (27%) and Colombia (23%), which can be explained by the following reasons: GlobalData's reserve information is based on the economic limit that this company considers and may differ from those of ECOPTROL and Colombia; the reserves of this model is the result of the sum of each one of the fields, while the ECOPETROL and Colombia reserves report is a general data; ECOPETROL's reserves include those reported in other countries, for example, 888 PJ correspond to the company's operations in the Permian basin of the United States (ECOPETROL, 2019b).

Table A.13. Reserves comparison between Colombia, ECOPETROL, and TIMES-O&G.

		Colombia (ANH, 2021c)	ECOPETROL (ECOPETROL, 2019b)	TIMES-O&G
Re	PJa (Mboe)	14.286 (2346)	11.528 (1.893)	10.467 (1.719)
Rg/Re	%	23%	27%	19.48%
Re/(O+GCOMM)	Years	6,0	7,8	7,5
Ro	PJa (Mboe)	11.059 (1.816)	8.416 (1382)	8.428 (1.384)
Ro/O	Years	6,3	7,2	8,2
Rg	PJa (Mboe)	3.227 (530)	3.113 (511)	2.039 (335)

Rg/ G_{COMM}	Years	8,1	10,4	5,6
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A.3.4 Hydrocarbon reserves and resources

In the previous section, the proven reserves (also called reserves P1¹⁷) of each sedimentary basin were established (see Table A.12 and Table A.13). However, no information related (for sedimentary basin, oilfields or ECOPETROL) to probable and possible reserves was found. Then it was decided to establish these parameters according to a relationship between proven reserves and these in the Colombia context. For this purpose, the data reported by the PEN in the low and medium scenarios were used and the relationship between them was established (Table A.14), for example, for 1 PJ of reserves P1 there are 1.41 PJ of P3 reserves.

Table A.14. Relation between proven, probable, and possible reserves in low and medium scenarios.

		Low scenario (Px/P1)	Medium scenario (Px/P1)
Reserves P1	PJ/PJ	1,00	1,00
Reserves P2	PJ/PJ	1,26	1,31
Reserves P3	PJ/PJ	1,41	1,54

Note: based on the data presented by the PEN (UPME, 2020b). Px refers, as the case may be, to P1, P2 and P3.

The P2 and P3 reserves of each sedimentary basin and of the model were calculated knowing the P1 reserves (see Table A.12) and their relationship with P2 and P3 (Table A.14). The results are presented in Table A.15 for each scenario. Note that in both scenarios the ratio of gas reserves to total reserves is always the same (19.16%), since the ratio between P1, P2 and P3 was assumed to be the same for each sedimentary basin.

¹⁷ Reserves P1 is proven reserves; Reserves P2 is proven reserves + probable reserves; P3 is proven reserves + probable reserves + possible reserves. Notice that reserves P1 – Reserves P2 means probable reserves and Reserves P3 – Reserves P2 means possible reserves.

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Table A.15. Reserves P1, P2, and P3 of the TIMES-O&G model.

		Low Scenario			Medium Scenario		
		Natural gas represents 19.48% of the total reserves			Natural gas represents 19.48% of the total reserves		
		Crude Oil	Natural Gas	Total	Crude Oil	Natural Gas	Total
Reserves P1	$\frac{P}{J}$	8.428	2.039	10.467	8.428	2.039	10.467
Reserves P2	$\frac{P}{J}$	10.629	2.572	13.201	11.067	2.678	13.745
Reserves P3	$\frac{P}{J}$	11.899	2.879	14.778	12.975	3.140	16.114

However, the TIMES-O&G model also wanted to represent the exploration and exploitation of new basins, as is also assumed by the PEN through resources named yet to find (YTF). This model will assume that there is a field (CAM8) that gathers all the fields that will be discovered and exploited in the future. No specific information about YTF was found for the reference company, then it was decided to establish again a relationship between P1 reserves and Yet to Find at the Colombian level (see Table A.16) and apply that relationship with the P1 reserves of the model (see Table A.17).

Table A.16. Relation between YTF and P1 in low and medium scenarios in the PEN [61].

		Low Scenario (YTF/P1)		Medium Scenario (YTF/P1)	
		Crude Oil	Natural Gas	Crude Oil	Natural Gas
Yet to find (YTF)	$\frac{P}{J}/\frac{P}{J}$	0	0,211	0,83	0,868

Note: YTF and P1 refers to Colombian context. For the calculation of the oil ratio, the information from the PEN was considered (UPME, 2020b), while for natural gas the information was obtained from the 2020 natural gas supply plan (UPME, 2020a).

Table A.17. Yet to find resources in the TIMES-O&G model.

		Low scenario			Medium scenario		
		Natural gas represents 100% of the total reserves			Natural gas represents 20.2% of the total reserves		
		Crude Oil	Natural Gas	Total	Crude Oil	Natural Gas	Total
CAM 8 (Yet to Find)	$\frac{P}{J}$	-	429	429	6.996	1.771	8.767

Finally, Table A.18 summarizes the P1 reserves -GlobalData data- and the P3 reserves that are included as input data in the model under two scenarios. It should be noted, that YTFs are assumed to eventually convert to reserves and are therefore considered in the model. It was established that the time to develop YTF resources is 5 years¹⁸ (UPME, 2020a; E. Yáñez et al., 2020b), then the production technologies will only be available from 2023.

Table A.18. Scenarios of reserves for each sedimentary basin modelled in TIMES-O&G.

	Reserves P1 (Rt)	P3 (Low scenario)	P3 (Medium scenario)
	PJ	PJ	PJ
CAM1	267	377	411
CAM2	2159	3049	3324
CAM3	6497	9173	10002
CAM4	45	63	69
CAM5	1059	1495	1630
CAM6	283	400	436
CAM7	158	223	243
CAM8	-	429	8767
Total	10467	15208	24882

A.3.5 Hydrocarbon production

In Colombia, 88% of the oilfields are produced through primary recovery, 11% comes from secondary recovery, and less than 1% comes from tertiary recovery (Castro et al., 2010, 2014). Then, it will be assumed that all production processes refer to primary production, that is, through energy consumption (related to the artificial lift system), without the injection of fluids for oil displacement and/or upgrading. The information on costs, specific GHG emissions (SGE) and electricity consumption of each process will be taken from studies that

¹⁸ The period of 5 years is established to a process CCS-EOR and the exploitation of ECOPETROL offshore fields according to UPME.

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have reported these data applied to the reference company (see Table A.19 and Table A.20)

(E. Yáñez et al., 2018; É. Yáñez et al., 2021).

Table A.19. Production cost of fossil fuels [54]

Stage	Cost, MUSD/PJ (USD/bl)
Finding	3,2 (19,5)
Development	1,3 (8)
Lifting	1,4 (8,7)
Transport	0,5 (3,3)
Refining	0,8 (4,8)
Dilution	0,7 (4,5)
Total	8 (48,8)
Conversion	0,1 (0,8)
Final	9,8 (59,6)

Table A.20. Electricity consumption and SGE breakdown for the production stage [46].

	Electricity consumption (PJ/PJ)	SGE (kt/PJ oil)
Production stage	0,01622	1,8
Wells	0,01058	0,3
Gras treatment	0,00122	0,4
Crude Treatment	0,00442	0,5
Power plant	0,01622	0,7

Note: Originally the specific energy consumption (SEC) is reported, however, for this study the necessary data is the electrical consumption, which was taken based on the assumptions of the article.

Table A.21 presents the parameters used to model each oilfield taking into account the following: the flaring was represented as the relationship between the gas that is flared and the total gas produced, based on information from the ANH balance for the base year (ANH, 2021b); the production cost of the existing fields (CAM1-CAM7) is the sum of the lifting and development processes, while for new fields (CAM8) the parameter corresponding to finding was added (see **Error! Reference source not found.**); the costs of electricity consumption and specific GHG emissions were taken the same for all fields based on the stage “wells” of **Error! Reference source not found.**

Table A.21. Parameters used to model the hydrocarbon production.

	Relation of flaring PJ/PJ	Cost production MUSD/PJ	Electricity consumption PJ/PJ	SGE Kt CO ₂ -eq/PJ
CAM1	0,00			
CAM2	0,01			
CAM3	0,63			
CAM4	1,00	2,74	0,01058	0.3
CAM5	0,16			
CAM6	0,16			
CAM7	0,02			
CAM8	0,02	5,94		

Note: data is based on **Error! Reference source not found.** y **Error! Reference source not found.**, except for relation of flaring that was calculated based on the ANH's information (ANH, 2021b)

Table A.10 establishes the total production of fluids for the base year, which in the model is interpreted as the maximum amount of fluids that can be produced. If only this condition is maintained, the model will assume that the maximum capacity is the same for all years of the time horizon (see extrapolation and interpolation options in Table A.2). It is a decision of the model if the production is done at the maximum capacity or at a lower one; in case the former happens, constant production would be forecast at full capacity - since hydrocarbons are in demand and there is the possibility of export (see section 2.4)- and then suddenly drop to zero as reserves are depleted.

To avoid the above, the decline in production of the oilfields will be represented, establishing a maximum capacity for each one. Global Data presents production projections of each oilfield¹⁹ that will be taken as a reference and that are presented in Table A.22, however, those projections are assuming the production of P1 reserves, while this model will take into account P3 reserves (see section 3.3), then they were normalized to ensure that there

¹⁹ The projections of each of the 35 selected fields were considered (see **Error! Reference source not found.**), then these projections were grouped according to the sedimentary count (**Error! Reference source not found.**).

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is the possibility of completely depleting the reserves, but keeping the decision of this to the model according to the optimization paradigm. For the non-existing fields (CAM8) there is no reference to decline projections, then the decline of the existing fields (CAM1-CAM7) is averaged, and a decline trend is obtained, then it was normalized to ensure that the resources can eventually be fully exploited. Since it is normalized on the reserves of each field, and there are two scenarios where the reserves are different (see Table A.18), then two projections are prepared for each scenario.

Table A.22. Projections of production of each sedimentary basin modelled

		2019	2020	2025	2030	2035	2040	2045	2050
CAM1	PJ	69	55	39	20	3	2	0	0
CAM2	PJ	377	370	221	112	52	23	13	7
CAM3	PJ	727	688	494	310	219	127	70	55
CAM4	PJ	6	5	4	3	2	1	1	1
CAM5	PJ	165	154	91	46	27	17	10	6
CAM6	PJ	30	28	20	13	9	6	4	4
CAM7	PJ	14	14	12	8	5	4	2	1
CAM8	PJ	0	0	126	73	45	26	14	10

Note: 2019 data are historical data reported by the ANH (ANH, 2021b), while data for future years is based on GlobalData projections (Global Data, n.d.; Offshore Technology, n.d.-b).

A.3.6 Hydrocarbon's separation

The previous process described allows the production of hydrocarbons (natural gas and crude oil), which are separated and treated on the surface to adapt their physical-chemical characteristics for their subsequent transport. This separation process is responsible for separating the fluids and their respective treatment according to relation between the gas and oil produced (G/O), and the process emission data were taken from the Table A.20, considering emissions both for the treatment of natural gas (0.40 Kt CO₂-eq/PJ) and crude oil (0.50 Kt CO₂-eq/PJ) for those fields that have a G/O ratio greater than 0.1, which would imply

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the significant presence of both fluids. The parameters finally used are presented in Table A.23.

Table A.23. Parameters used to model the hydrocarbon treatment.

	G/O PJ/PJ	SGE Kt CO ₂ -eq/PJ
CAM1	No oil production	0,40
CAM2	2,501	0,90
CAM3	0,003	0,50
CAM4	0,293	0,90
CAM5	0,030	0,50
CAM6	0,052	0,50
CAM7	183,267	0,40
CAM8-L	No oil production	0,40
CAM8-M	0,253	0,90

Note: Since the relationship between natural gas and the total fluids produced in different for CAM8 in each supply scenario (see **Error! Reference source not found.**), it was defined that CAM8-L refers to the CAM8 modelled in low scenario of supply while CAM8-M refers to the medium scenario.

A.3.7 Hydrocarbon transport

As explained in section 3.1, the transportation process is simplified and allows the connection of hydrocarbons from each field with crude oil and natural gas that can be used nationally. Table A.19 differentiates between the cost for the transportation of hydrocarbon and the cost of the diluent, then it was assumed that the latter would only be included in the fields that produce heavy and medium crude oil (according to Table A.9), while light oil only include transportation reference cost. Electricity consumption was defined the same for both the transportation of natural gas and crude oil.

Table A.24. Parameters used to model the hydrocarbon transport (E. Yáñez et al., 2018; É. Yáñez et al., 2021).

	Cost of dilution MUSD/PJ	Cost of transport MUSD/PJ	Electricity consumption PJ/PJ
CAM1	0		
CAM2	0		
CAM3	0,74	0,55	0,00236 (CENIT, 2020)
CAM4	0		

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CAM5	0,74
CAM6	0,74
CAM7	0
CAM8	0,74

A.3.8 LPG production in oilfields

Once the natural gas is separated, it can go to a processing plant -if there is a facility within the field- to produce LPG. It was reviewed which fields had process facilities and their capacity, as shown in Table A.25. This model does not consider the transportation of products other than natural gas and crude oil, therefore the LPG produced in oilfields can be used directly to meet demand, for import or for self-consumption. As well as the LPG supply plan(UPME, 2018c), a scenario is distinguished that considers the entry into operation of the Cupiagua plant and another scenario in which it is not.

Table A.25. Supply of LPG in sedimentary basins.

CAM	Oilfield	Capacity of processing LPG (with Cupiagua) Pja (bpd)	Capacity of processing LPG (without Cupiagua)
CAM1	-	-	-
CAM2	Cupiagua(BNamericas, 2019), Cusiana (Portafolio, 2011),	21,9 (14.800)	10,07 (6.800)
CAM3	Apiay(Castiblanco, 2011)	1,2 (800)	1,2 (800)
CAM4	-	-	-
CAM5	-	-	-
CAM6	Dina (MINMINAS, 2022)	0,3 (176,7)	0,3 (176,7)
CAM7	-	-	-

Note: The Floreña oilfield has facilities to produce LPG, however, different reports indicate that future production from this field will be null due to administrative processes and therefore it was not taken into account (MINMINAS, 2022; UPME, 2018c).

A.3.9 Self-generation and purchase of electricity

The processes of the production stage require electricity, which can be purchased from the national grid or self-generated on site. There is no detailed information for each field or the reference company, therefore, the UPME 2014 self-generation and cogeneration

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inventory was used (UPME, 2014). This study distinguishing between the production and transportation stage, but does not detail in the data for ECOPETROL, then, it was decided to assume the following: since ECOPETROL controlled 57% of the production of the companies reported in the study, it was assumed that the installed capacity of the reference company is 57% of the total reported; In order to know the installed capacity of each sedimentary basin, the data reported from each department was related to each sedimentary basin -e.g.: the data reported for the department of Meta were assumed for the Llanos Orientales basin-. In this way, the inventory of the installed self-generation capacity for the model is stipulated as shown in Table A.26.

Table A.26. Installed capacity for self-generation in each sedimentary basin.

Oilfield	Production stage (MW)				Transport stage (MW)		
	LPG	Natural Gas	Crude Oil	Diesel	Natural Gas	Crude Oil	Diesel
CAM1	0	34,25	0	0	14,78	0	0
CAM2	20,0	150,1	0	11,4	3,62	0	13,57
CAM3	0	131,9	48,3	11,4	0	14,48	13,57
CAM4	0	0	21,2	10,03	0,47	1,88	3,52
CAM5	0	19,45	41,4	19,6	1,21	4,83	9,05
CAM6	0	2,3	19,7	9,3	0,47	1,88	3,52
CAM7	0	0,3	0	8,9	0,13	0,54	1,01

Note: Adapted from UPME (UPME, 2014).

According to the UPME self-generation inventory, the main type of technology for generation based on natural gas is combustion turbines and internal combustion engines for liquid fuels(UPME, 2014). Based on this, the parameters of the installed self-generation technologies are reported in Table A.27. The economic parameters (CAPEX, FIXOM and VAROM) of natural gas were taken from the Annual Technology Baseline for Electricity developed by NREL(NREL, 2021), assuming the "Gas-CT" technology in the moderate scenario, while data of liquid-based generation, The Palgrave Handbook of International

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Energy Economics with diesel-based technology was used (Farnossh, 2021). According to the NREL, the useful life of these technologies is 30 years (NREL, n.d.); however, the date of installation is unknown, so it will be assumed that they were all installed in 2003, the year in which the UPME mentions that there was a significant increase in self-generation capacity in the oil sector (UPME, 2014); In this way, if the base year is 2019, all the technologies would have a remaining useful life of 13 years. Finally, the efficiency data were taken as the average of the efficiencies reported in the LEAP model for self-generation in the period 2010-2019 (Das et al., 2020), and all installed self-generation technologies assumed an average maximum utilization factor of 75%, as already used by a study for the national grid (E. Yáñez et al., 2020b).

Table A.27. Parameters for existing capacity of the self-generation based on fossil fuels.

Process	EFF %	CAPEX USD/KW	FIXOM USD/KW	VAROM USD/KWh	LIFE years
Based on Natural Gas (CT)	37.6%	936	21	0.00495	13
Based on Crude oil	35.8%	1150	20	0.014	13
Based on Diesel	35.6%	1150	20	0.014	13
Based on LPG	35.9%	-	20	0.014	13

Note: EFF refers to efficiency, FIXOM refers to fixed operation and maintenance expenses and VAROM refers to variable operation and maintenance expenses; LIFE refers to useful life. Data taken according to what was mentioned in the previous paragraph.

The foregoing implies that no later than 2032, investment must be made in new self-generation capacities to continue feeding hydrocarbon production with electricity -if it is optimal compared to buying directly from the national grid-. In fact, it is assumed that CAM8 -the oilfield that represents new discoveries- it is assumed that there are no installed capacities, then in 2023 investment in new capacities must be made. Then, thermal, and renewable technologies are proposed, with three levels of development every 10 years starting in 2020. Data for natural gas, solar and wind energy generation was based on the Annual Technology Baseline for Electricity developed by NREL, which presents three

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projection scenarios (conservative, moderate, advanced) (NREL, n.d., 2019); natural gas technology is combustion turbine (CT). In addition, the steam turbine fuel oil Conventional technology was included, taking data from the PRIMES model-18, since fuel oil is a fuel considered in this study with an available factor of 35% (Capros & Evangelopoulou, 2018). The diesel and crude oil-based technologies cited in Table A.27 were also available.

Table A.28. Techno-economics parameter for new generation technologies.

Scenario	PROCESS	Year	CAPEX, USD/Kw	FIXOM, USD/Kw	VAROM, USD/MWh	EFF, %	LIFE, year	
-	HFO	2020	1332	23	3,1	35%	40	
		2020	928	21	3	35%	30	
	GAS-CT	2030	846	21	3	35%	30	
		2040	800	21	3	35%	30	
	Moderate	Solar - Utility PV	2020	1378	23	0	100%	30
			2030	776	17	0	100%	30
		2040	707	16	0	100%	30	
		Land-based Wind	2020	1392	43	0	100%	30
			2030	950	39	0	100%	30
			2040	855	36	0	100%	30

Note: EFF refers to efficiency, FIXOM refers to fixed operation and maintenance expenses and VAROM refers to variable operation and maintenance expenses. Data taken according to what was mentioned in the previous paragraph.

The solar and wind energy utilization factor was not taken from the NREL report, but instead, the Renewable Ninja tool was used (Pfenninger & Staffell, 2016; Staffell & Pfenninger, 2016), which using the 2019 MERRA-2 (global) database to calculate the average capacity factor annual for a specific location; then, the location of each of the oilfields (see Table A.8) was taken and the same assumptions made by Younis et al. in the use of this tool in the Colombian context were made (Younis et al., 2021): for solar energy, tilt and azimuth angles of 35° and 180 ° and system losses of 10% were assumed; For wind energy, an 80m hub height and the Vestas V9 2000 turbine model were assumed. The results

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were computed for each existing oilfield (CAM1-CAM7), while for the field that represents new discoveries (CAM8), since it did not have a defined location, it was decided to take the average of the existing fields.

Table A.29. Mean capacity factor for solar and wind energy.

Oilfield	Solar energy	Wind energy
CAM1	16,5%	38,7%
CAM2	15,7%	6,0%
CAM3	15,3%	4,3%
CAM4	14,7%	2,2%
CAM5	14,4%	1,0%
CAM6	15,6%	6,8%
CAM7	15,4%	5,3%
CAM8	15,4%	9,2%

Note: data computed using the above assumptions.

Additionally, solar power generation projects announced by the Ecopetrol group was taken into account for the existing capacity, totaling 82 Mwp, located in the department of Meta, with 21 MWp inaugurated in 2019 and 61 Mwp projected to 2022(ECOPETROL, 2021b). These projects use the technical-economic data from Table A.28 with a moderate scenario at the 2020 level; since the projects are located in areas covered by CAM3, the utilization factor of that oilfield was used.

In the event that the self-generation capacity is not sufficient to cover the electricity demand of the fields, then another option different from the expansion of the installed capacity is the purchase of electricity from the national grid based on the established prices (see section 2.4).

A.4. Conversion module

A.4.1 RES of conversion module

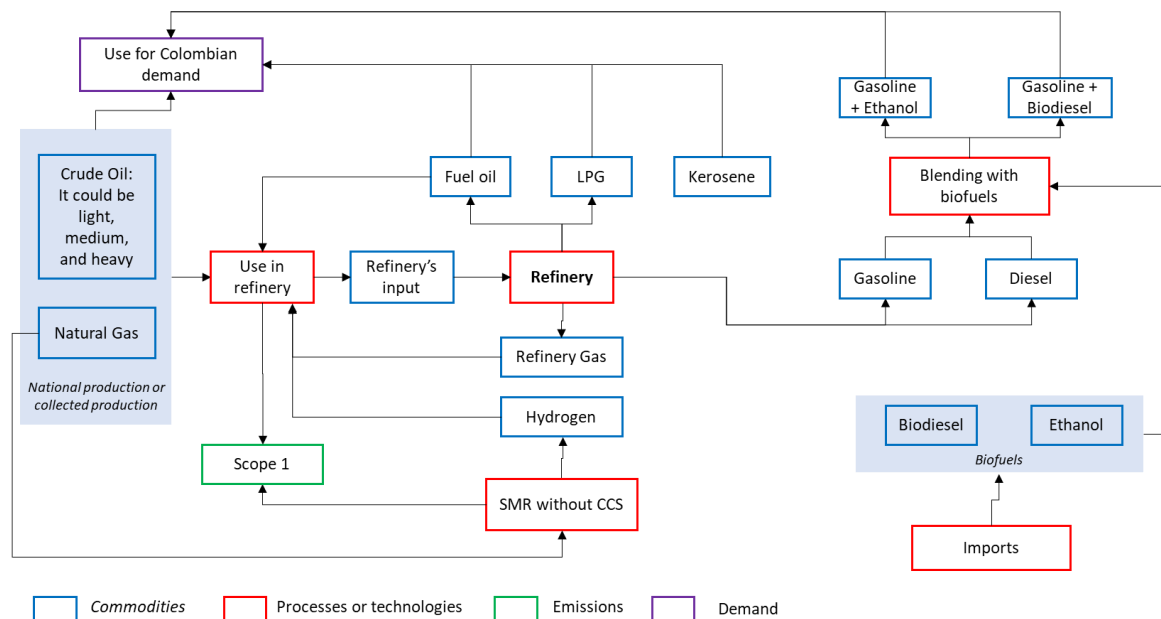
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The TIMES-O&G model seeks to represent the transformation of hydrocarbons into fossil fuels that are demanded by the Colombian consumer sectors. In turn, the differences between the supply and demand of fuels constitute a market subject to export and import prices. The Cartagena and Barrancabermeja refineries were included, which constitute approximately the entire Colombian refining capacity (ECOPETROL, 2019a).

Both refineries were modeled according to Figure A.4. The refining process requires fuel inputs -including hydrogen- and allows the production of fossil fuels; some of them are self-consumed by the refining process, as is the case of refinery gas. It should be noted that the consumption of fuels used in the refinery for cogeneration processes and hydrogen production release GHG emissions that are accounted for in scope 1.

The fossil fuels produced can be used to meet national demand or to be exported, however, gasoline and diesel must go through a blending process with biofuels to have a mixture according to the percentage regulated in the country and only then can the above be used to supply the Colombian demand.

Figure A.4. RES of hydrocarbon transformation in TIMES-O&G.



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Note: Only the import of biofuels was included in this figure for simplification, but it should be noted that all fuels can be exported and imported according to the provisions of section 2.4.

A.4.1. Refinery inputs

In general, the composition of the diet at the Cartagena refinery is 70% heavy crude and 30% light crude, while for the Barrancabermeja refinery the diet is the reverse (Morillo, 2020). However, the diets presented in Table A.30 were used, which are consistent with the study distinction (light, medium and heavy crude oil). The data from the Cartagena refinery were taken from a public response from ECOPETROL to UPME on the liquid fuel supply study 2018 (UPME, 2019a), while the data from the Barrancabermeja refinery was calculated based on the assumptions²⁰ of the fuel supply plan liquid fuels of 2021 and 2018(UPME, 2019a, 2021c).

Table A.30. Refinery diet in the TIMES-O&G.

Type crude oil	Cartagena refinery	Barrancabermeja refinery
Heavy crude oil	60%	30%
Medium crude oil	25%	47%
Light crude oil	15%	23%

In addition to crude oil, other fuels are also required for certain processes, including cogeneration. Table A.31 presents the input of other fuels based on the oil load. The ratio of hydrogen, natural gas and refinery gas of the Cartagena refinery were calculated based on the balances presented in the environmental impact study of the refinery (REFICAR, 2020), while for the Barrancabermeja's refinery the rations were calculated based on the simplified balance and data presented by Yañez and collaborators of the refinery in question (É. Yañez

²⁰ It was assumed that the share of light crude was 30% (Morillo, 2020), and that the share of medium and heavy crude was such that the mix input was at least 24 API (UPME, 2021c).

et al., 2021). Regarding the LPG ratio, for both refineries the self-consumption the fuel was taken from the LPG declaration in 2019²¹ (UPME, 2019b).

Table A.31. Input of fuels for the refinery in relation to the input of crude oil.

Other inputs		Cartagena Refinery	Barrancabermeja Refinery
Hydrogen	PJ/PJ (t/kbl)	0.00933 (0.473)	0.00129 (0.0655)
Natural gas	PJ/PJ (MPC/kbl)	0.03817 (0.23)	0.04007 (0.24)
Refinery gas	PJ/PJ (MPC/kbl)	0.03372 (0.20)	0.02398 (0.15)
LPG	PJ/PJ (kbl/kbl)	0.00149 (0.0022)	0.00199 (0.003)
Fuel oil	PJ/PJ (kbl/kbl)	-	0.01267 (0.014)

Note: The data was calculated using the aforementioned sources (REFICAR, 2020; É. Yáñez et al., 2021). All ratios are expressed as PJ of fuel over PJ of crude loaded to refinery (original unit over thousands of barrels of crude).

Technical-economic parameters to model the refinery are presented in the Table A.32.

The nominal capacities, as well as the maximum utilization factor for the time horizon, were taken from the indicative plan for the supply of liquid fuels 2021(UPME, 2021c); for the base year, the utilization factor was adjusted based on the ECOPETROL report for that year. The efficiency was calculated knowing the load to the refineries and the fuel production (see Table A.34). Finally, the refining cost was taken from the Table A.19 (É. Yáñez et al., 2021). For these scenarios, the expansion of the Cartagena refinery was not considered because this is an assumption shared by the studies carried out by UPME(Morillo, 2020; UPME, 2021c).

Table A.32. General parameters to model refineries.

General parameter		Cartagena Refinery	Barrancabermeja Refinery
Capacity (UPME, 2021c)	P _{ja} (kbl/d)	366 (165)	555.5 (250)
Utilization factor in 2019 (ECOPETROL, 2019b)	%	94%	87%

²¹ The LPG declaration presents the gas that is used in the operation, then this value and the crude oil load of 2019 was considered to obtain the relationship.

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Utilization factor in future (UPME, 2021c)	%	95%	90%
Efficiency	%	83.7% (REFICAR, 2020)	89.9% (UPME, 2021c)
Cost (É. Yáñez et al., 2021)	MUSD/PJ (USD/bl)	0.79 (4.81)	

Note: Capacity refers to the maximum amount of crude oil that could be refined while efficiency refers to the conversion of crude oil into other fossil fuels.

A.4.2. Hydrogen production in refineries

The model assumes that there is sufficient capacity to produce the hydrogen currently demanded in each of the refineries through SMR. Table A.33 details the technical-environmental parameters of this technology. The emission factors of the technologies that use natural gas are determined by the combustion of natural gas.

Table A.33. Hydrogen production options for both refineries [106].

Technology	Parameter	2020	2030	2050	
Natural gas reforming	CAPEX	MUSD/PJ	28,86	28,86	28,86
	Eff	%	0,76	0,76	0,76
	Annual OPEX	MUSD/PJ	1,36	1,36	1,36
	Utilization factor	%	95%		
	Lifetime	years	25		

Note: The data for 2020 and 2050 were taken in reference to the "Today" and "Long term" periods of the IEA report.

A.4.4. Refinery outputs

The fuels that are produced in the refineries and their proportions were established based on the balances reported for each of the refineries under normal operation (Morillo, 2020; UPME, 2021c). As in the studies of the indicative plan for the supply of liquid fuels and the PEN, the outputs of the refinery remain constant in the period of time.

Table A.34. Refinery outputs in TIMES-O&G.

Type crude oil	Cartagena's Refinery (REFICAR, 2020)	Barrancabermeja's Refinery (UPME, 2021c)
Gasoline	23.32%	31.05%
Diesel	63.37%	33.54%
Kerosene	5.71%	8.39%

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LPG	2.65%	1.63%
Fuel Oil	0.91%	22.15%
Refinery Gas	4.03%	3.24%
Avigas	0%	0%

Note: the percentages presented refer to energy relations.

However, flexible outputs from the refinery are also proposed, so that the TIMES-O&G model optimizes what the outputs should be based on demand and the balance of imports and exports. For this, the maximum and minimum percentages of fuel output from each refinery were taken into account according to what was reported in the LEAP model during the period 2016 onwards; previous dates were not taken since the Cartagena refinery was not in operation due to its modernization that ended in 2015.

Table A.35. Refinery flexible outputs in TIMES-O&G.

Type crude oil	Cartagena's Refinery (REFICAR, 2020)	Barrancabermeja's Refinery (UPME, 2021c)
Gasoline	19.80% - 23.32%	29.85 -32.14%
Diesel	34.0% - 63.37%	32.91% - 34.54%
Kerosene	5.60% - 12.38%	7.96% - 8.05%
LPG	1.0% - 1.80%	1.63%
Fuel Oil	0.91% - 9.90%	15.80% - 22.15%
Refinery Gas	0% - 4.03%	0% - 3.24%
Avigas	0% - 0.1%	0% -0.1%

Note: the percentages presented refer to energy relations.

A.4.5. Blending with biofuels

For the base year, the blend percentage of biofuels was regulated by resolutions 40666 and 40730 (MINMINAS, 2019; Resolución 40730 de 2019, 2019), which estimated 10% by volume for both ethanol and biodiesel. This percentage was considered for the updating -or reference scenario-, while for the other scenarios the possibility of increasing this percentage was considered in accordance with those established by the PEN(UPME, 2020b). This assumption will begin in 2025, that is, in the analysis of the first six years of the model, all the scenarios share the same blend percentage.

Table A.36. Percentage of biofuels in gasoline and biodiesel blends.

Biofuel	Updating	Upgrading	Inflection	Disruptive
Ethanol %energy (%vol)	5,76% (10%)		7,60% (13%) – 8,85% (15%)	
Biodiesel %energy (%vol)	9,37% (10%)		12.20% (13%) – 14,10% (15%)	

Note: the percentage shown refers to the amount of biofuel in the mixture.

A.5. Policies

A.5.1 Carbon tax

Colombia has regulated the carbon tax through article 222 of Law 1819 of 2019 and establishes a price for the emission of GHG through the combustion of fossil fuels (Ley 1819 de 2016, 2016). In 2022 the price of this tax was established at approximately 4.96 USD/t CO₂-eq (IETA, 2022), however for this study a tax of 7 USD/t CO₂-eq (0.007 MUSD/kt CO₂-eq) will be assumed to be aligned with related ECOPETROL studies (E. Yáñez et al., 2018).

In the PEN document, a carbon tax was established equally for the four scenarios, and it was included directly in the fuel price, while in this study it was calculated considering the emissions from combustion processes within scope 1, 2, 3. However, the following should be considered:

- The carbon tax for biofuels will not be taken into account in accordance with the provisions of paragraph 3, article 221 of law 1819 of 2019.
- Natural gas that is consumed by sectors of national consumption is not covered by the tax. carbon according to paragraph 4, article 221 of law 1819 of 2023. Natural gas that is used for self-generation or consumption in refineries is covered by the tax.
- Fuel exports count as scope 3 emissions (section 2.5) but are not covered by the carbon tax in accordance with paragraph 4, article 222 of law 1819 of 2023.

Appendix B: Validation of TIMES-O&G model

This document is part of the article “Assessment of the Colombian long-term energy planning scenarios for the national hydrocarbon value chain: Insights from the TIMES-O&G model” and contains the results of reference scenario of the TIMES-O&G model, which is contrasted with other similar studies.

B.1. Considerations for the validation process

The TIMES-O&G model seeks to represent the typical activities of a company dedicated to the O&G industry in the Colombian context, taking ECOPETROL as a reference, but without limiting itself to representing this company. There is no predictive model of this type developed for this company or a similar one, which is why a direct comparison of this model cannot be made, however, TIMES-O&G model can be validated through its comparison with historical data predictions made for the Colombian, as show in Table B.1.

Nevertheless, the following considerations should be taken into account:

- It should be noted that although the reference company (TIMES-O&G) is present in all stages of the O&G value chain, the results for the company may be far from those who focus on Colombia.
- There is a TIMES model developed for Colombia (TIMES-CO-9), but to date no publication or report has been found that presents its results (CREE, n.d.). In addition, there is a model extended to biomass economics called TIMES-CO-BBE, but it does not present focused results for the O&G sector. That is, it will not be possible to make a comparison with other TIMES models applied to the Colombian context.

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- The approach of some of the predictive models carried out for Colombia are different from a TIMES model, for example LEAP is a simulation tool, while TIMES is based on the optimization paradigm, and therefore the expected results may be different. The level of detail of the TIMES-O&G model is different from that of other models. For example, the LEAP model developed for the PEN focuses on the analysis of consumption sectors (demand), while the TIMES-O&G model delves into the detail of supply and conversion.

Table B.1. Main studies for comparison with TIMES-O&G

Report	Organization	Type	Context	Scope	Time horizon ²²	Objective
Indicative liquid fuel supply plan 2018, 2021. ²³ (UPME, 2018b, 2021c)	UPME	Simulation model (built for this report)	Colombia	Only liquids fuels (mainly diesel, LPG, gasoline, and kerosene)	2020-2044	Define the balance of import and export of fuels. Ensure that the infrastructure exists for the supply in the country.
Technical study for the plan of supply natural gas (UPME, 2020a)	UPME	Technical-economic analysis	Colombia	Only natural gas	2019-2040	Identify self-sufficiency of natural gas in the country. Define infrastructure requirements for natural gas supply.
Indicative Plan for the Supply of Liquefied Petroleum Gas LPG (UPME, 2018c)	UPME	Technical-economic analysis	Colombia	Only LPG	2018-2035	Carry out an analysis of supply and reliability of LPG for Colombia.
National energy plan 2020-2050 (UPME, 2020b)	UPME	Simulation model (LEAP)	Colombia	Energy sector	2020-2050	“Define a long-term vision for the energy sector and identify possible ways to achieve it.

²² It refers to the time horizon of the model results or historical data reported.

²³ There are two versions for this report, and each of them presents relevant information to the study, for which both will take into account.

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						It is not an exercise in forecasting what the future will be like, but in exploring alternatives by which it can be shaped.”
Statical bulletin of mines and energy 2016 – 2020 (UPME, 2021a)	UPME, MINMINAS	Historical data	Colombia	Oil, natural gas, electricity		Present the most relevant statistics of the energy sources considered.
System analysis of the bio-based economy in Colombia: A bottom-up energy system model and scenario analysis (Younis et al., 2021)	Younis et al.	TIMES-CO-BBE model	Colombia	Energy sector.	2015-2050	Explore the potential contribution biomass economy to the low carbon supply of energy and chemicals in the Colombian context.
Integrated sustainable management report (ECOPETROL, 2019b, 2020, 2021b)	ECOPETROL	Historical data	O&G company	O&G value chain	2019, 2020, 2021.	Present company statistics and milestones for each base year.
TIMES-O&G (This study)		TIMES-O&G	Conceptual company of O&G	O&G value chain	2019-2050	Represent in detail operations of the company O&G ²⁴ in the Colombian context. Model decarbonization scenarios and analyze the implications.

B.2. Reference scenario description

The validation of the model took the reference scenario of the TIMES-O&G model, named business as usual (BAU) scenario. Since the PEN has four scenarios, the base scenario

²⁴ It should be noted that the TIMES-O&G model represents the typical operations of an "O&G company" in Colombia and does not directly represent ECOPETROL (see more detail in annex 1, section 1).

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called updating scenario was selected to contrast it with the TIMES model. Table B.2 presents a general comparison between the reference scenarios proposed by the PEN and the TIMES-O&G model; it should be noted that the characteristics of the PEN refer to the Colombian context, while the TIMES model refers to the context of the conceptual O&G company. More detail is presented on each of the characteristics of the TIMES-O&G model can be consulted in annex 1 of this study.

Table B.2. Comparisons between PEN and TIMES-O&G reference scenario.

	PEN - Updating	TIMES-O&G (BAU)
Reserves	Medium scenario	Medium scenario
Resources	YTF + YNC	YTF
Extractive process	No detail	Detailed by sedimentary basins
Declination	Production declaration	Global Data
Blending for fuels	10% (no future increase)	10% (no future increase)
Fuel's prices projections	UPME reference	AEO -2019 – Reference case
Import/Export prices relation	1,2	1,23
Demand	Updating - UPME	Updating – UPME (only fuels related to O&G industry)
Refinery Outputs	Fixed	Flexible
Renewable energies	Current plan	Current plan
Hydrogen production	Grey	Grey (natural gas)
CSS	No	No
Emissions	Scope 3	Scope 1, 2 and 3 (only fuels related to O&G industry)

B.3. Validation

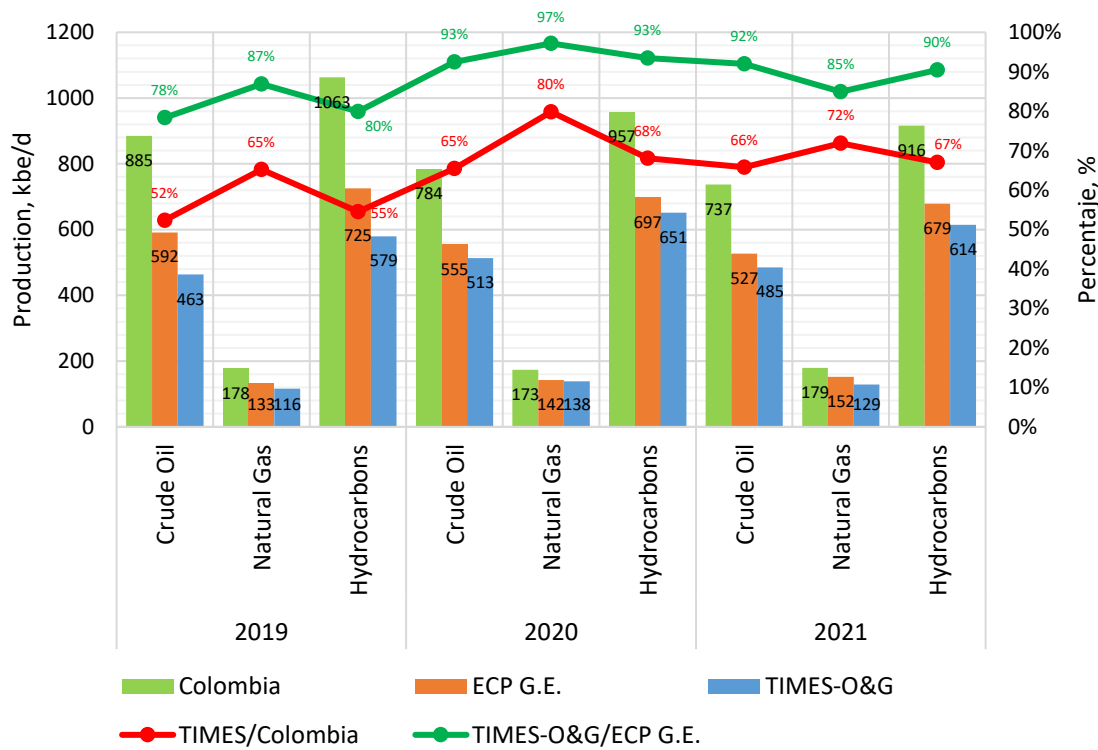
B.3.1 Supply of hydrocarbons

The TIMES-O&G model effectively represents at least 80% and 55% of the production of ECP and Colombia respectively not only for 2019 but also for 2020 and 2021

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(see Figure B.1). The increase in participation for the 2020 period corresponds to two factors: starting this year, the Guajira sedimentary basin (Chuchupa and Ballena oilfields) was included, since it was not until this year that the oilfields were operated by one of ECP's subsidiaries(HOCOL, 2020); As of this year, the production data in the TIMES-O&G model were obtained according to the GlobalData decline curves (Global Data, n.d.), which did not take into account the decrease in production caused by the COVID-19 pandemic.

Figure B.1. Comparison of hydrocarbon supply with historical data.



Note: The data for the production of Colombia and the Ecopetrol group were taken from the UPME statistical bulletin (UPME, 2022b) and Integrated Sustainable Management reports of the company (ECOPETROL, 2019b, 2021b), respectively.

B.3.1.1 Supply of crude oil

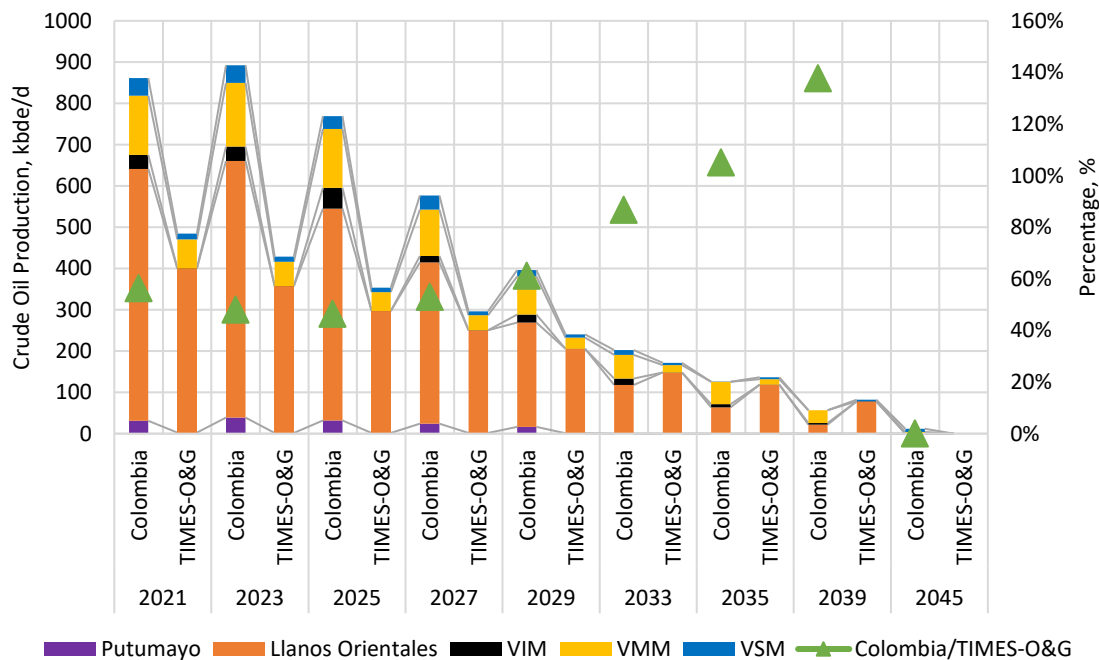
Figure B.2 seeks to compare the declared production for Colombia and the estimated production for the TIMES-O&G model by sedimentary basins, since no projection was found for the oilfields operated solely by ECP. This implies comparing the total production of a

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basin with the production of oilfields in which the O&G company has a stake and producing differences between the results of Colombia and TIMES-O&G. For example, for the base year, ECP production in the department of Putumayo presented only 26% of the total reported for this region(ANH, 2021b); Furthermore, not all the fields in which ECP has operations were included in the model TIMES-O&G due to lack of information. For the above two reasons, appreciable differences can be seen in some sedimentary basins such as the Putumayo and VIM basins.

Despite this, it is observed that the Llanos Orientales basin continues to be the one with the highest participation both for Colombia and for the TIMES-O&G model followed by the VMM and VSM basin, a trend that is valid not only for the base year but for the period presented. Both estimates show that oil production for 2045 is estimated to be approximately zero.

Figure B.2. Crude oil supply by sedimentary basins.

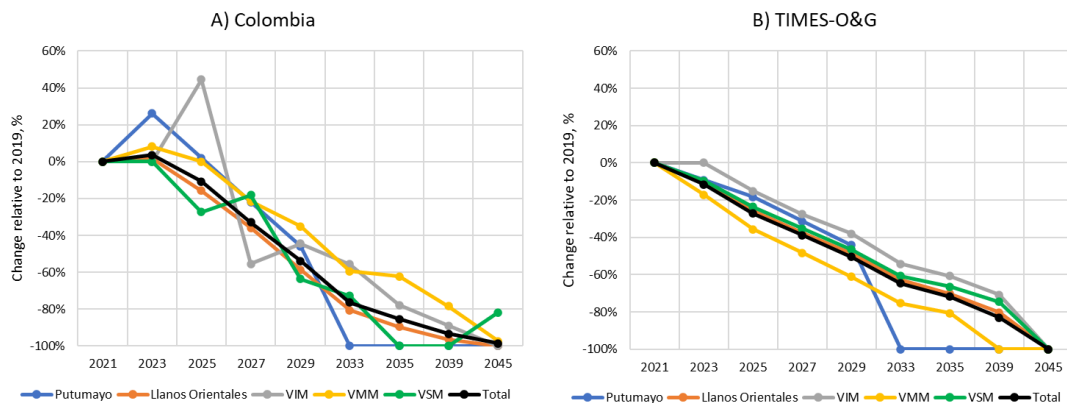


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Note: Data for Colombia were taken from the UPME projections in the 2021 liquid fuel supply plan – figure 4-2 (UPME, 2021c). In the same way that UPME does not consider new discoveries (Yet to find resources), neither do the results presented to TIMES-O&G.

However, in the previous graph it can be seen that the production of the O&G company with respect to Colombian production changes from 2033 (an increase from 61% to 87%) and for the years following 2035, the production of the TIMES- O&G is even higher than Colombia's. This occurs due to differences in the production decline of each estimate. The Figure B.3 shows that production in 2023 in Colombia increases 3% due to the increase in the Putumayo and VIM basins, while in the TIMES-O&G model production for that year falls by 11% and the production of all basins it always decreases with time; This implies a greater depletion of short-term reserves for Colombia than for the TIMES-O&G model. Even so, as of 2023, the decline in Colombian production is more pronounced than for TIMES-O&G, to the point that by 2029, Colombian production decreased 54% compared to 2021 compared to a 50% decrease for the model TIMES-O&G.

Figure B.3. Change in sedimentary basin production relative to 2021.



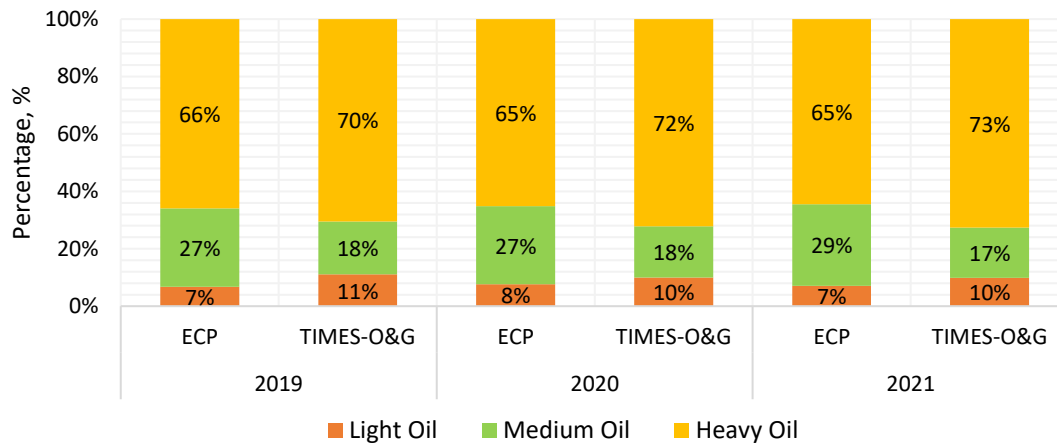
Note: This calculation used the same data as those used in **Error! Reference source not found.**

However, it is important to distinguish the production of crude oil by its quality, which is associated with its API gravity. Figure B.4 compares crude oil production according to its API gravity between ECP and the modeled O&G company. It can be seen that in both

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cases, the production of light crude varies between the range of 7-11%, being the type of crude less offered. The main difference occurs in the amount of medium crude, since for ECP the production of this type of crude represents between 27-29% in comparable years, while, according to the TIMES-O&G model, this type of crude represents between 17-18% of the total production. Even so, the results share the fact that the most common type of crude is heavy crude, which represents at least 65% and 70% of the production of ECP and the TIMES-O&G model.

Figure B.4. Comparison of crude oil supply by type of crude oil with historical data.



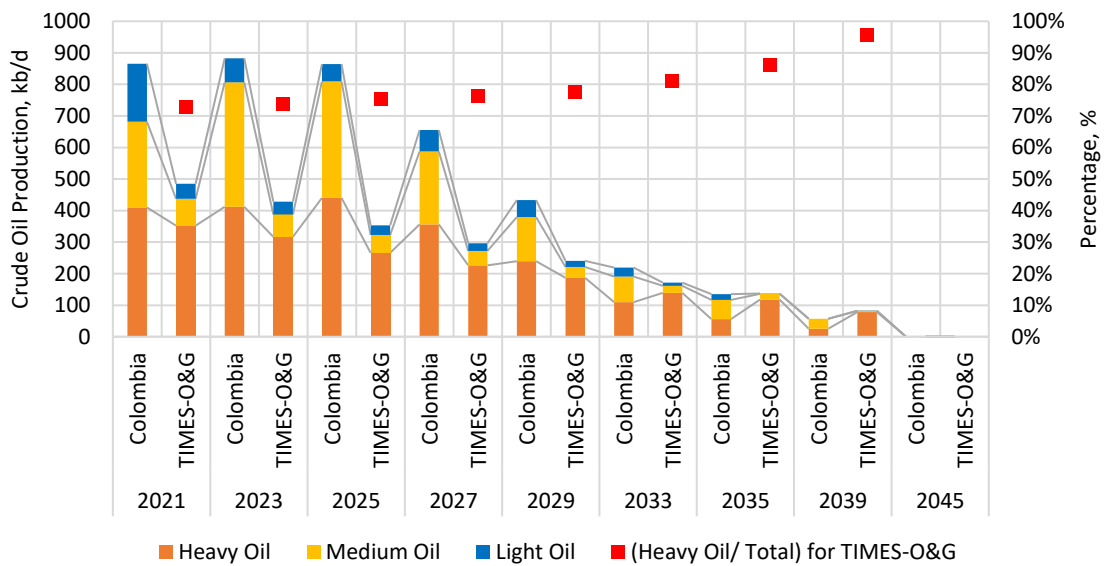
Note: The data for ECOPETROL was taken from the information in the company's quarterly reports (ECOPETROL, 2023).

On the other hand, Figure B.5), presents the projection of crude oil production according to API gravity for Colombia and for the O&G company; no similar estimation was found for ECP that will serve as a comparison. The results show the predominance of heavy and medium crude for both Colombia and the O&G company, however it is observed that the company's percentage of heavy crude is always greater than 70%, while for Colombia it is a maximum of 55%. This difference may have been due to the selection of fields in the TIMES-O&G model, since the fields with the highest oil production were taken, and in

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Colombia these correspond to heavy oil crude: of the 20 departments that currently extract crude oil, only one extracts light oil, 5 extract medium oil and the other 10 extract heavy oil (EITI COLOMBIA, 2017). It should also be taken into account that in Colombia there are no values of heat value and emission factors for each type of crude according to their classification by API gravity, therefore, it was assumed that all crudes shared these two parameters.

Figure B.5. Crude oil supply by type of crude oil.



Note: Data for Colombia were taken from the UPME projections in the 2021 liquid fuel supply plan – figure 4-1 (UPME, 2021c). In the same way that UPME does not consider new discoveries (Yet to find resources), neither do the results presented to TIMES-O&G.

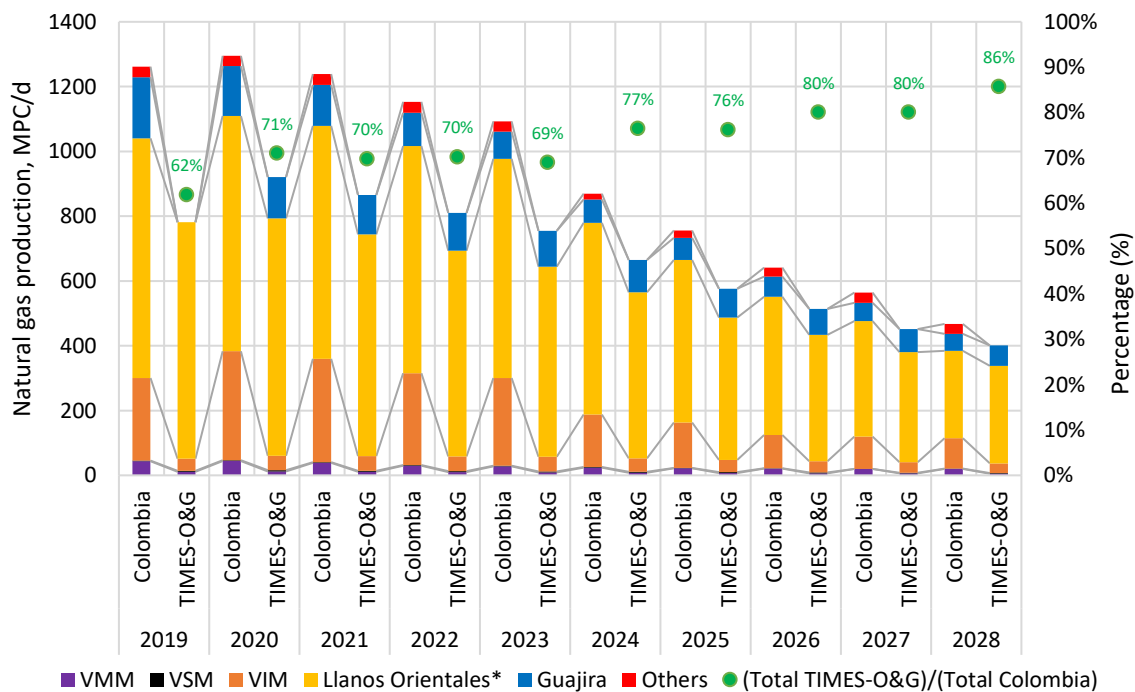
B.3.1.2 Supply of natural gas

The Figure B.6 shows the comparison of natural gas production by sedimentary basins. Again, the selection of fields for the O&G company in some sedimentary basins affects the comparison with the results of Colombia, of the 23 fields that are taken into account for Colombia, only 3 of them are operated by ECP and represent only 21.8 % of the total production of this basin, for this reason differences can be observed between the

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estimates for Colombia and for the TIMES-O&G model. In addition, there are two other sources of error from the modeling point of view: the production and decline data are given in volumetric units, which, to be entered into the model, were converted using the same calorific value for all the fields due to the fact that they were not found detailed information for each field; some oilfields produce both oil and natural gas, which are related by the gas oil rate (GOR), and the latter remained constant over time in this model, although it actually varies with pressure drop -which in turn occurs due to the production of hydrocarbons-. Despite this difference, it continues to be representative of the other sedimentary basins, as well as the participation of the O&G company with respect to national production that varies between 71% and 86% for the period 2020 - 2028.

Figure B.6. Natural gas supply by sedimentary basins.



Note: Data for Colombia were taken from the UPME 2020 natural gas supply plan, graph 1-7(UPME, 2020a). Others refers to Sinu San Jacinto, Catatumbo, Cesar Ranchería and Caguán Putumayo basins. In the same way that UPME does not consider new discoveries (Yet to find resources), neither do the results presented to TIMES-O&G.

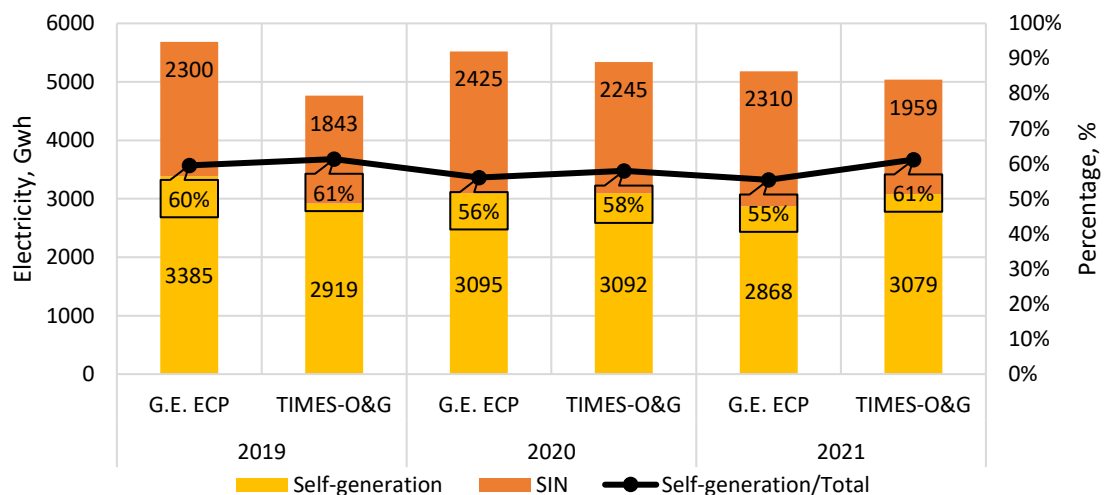
*In TIMES-O&G model the basin of Llanos Orientales groups the Cordillera Oriental basin (see annex I, section 3.2, table 9).

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B.3.1.3 Power generation

In the TIMES-O&G model, the processes associated with the production and transportation of hydrocarbons consume electricity that can be self-generated and/or purchased from the national grid. Using the self-generation inventory in 2014 of the UPME, the installed self-generation capacity was defined (UPME, 2014). It should be noted that there are no models that estimate how electricity consumption and self-generation of the oil sector in Colombia will behave to compare with the projections of the TIMES-O&G model. Hence, Figure B.7 seeks to compare the results of electricity consumption of and the company represented by the TIMES-O&G model with available historical data from ECOPETROL. Self-generation in the O&G company is in the range of 58% and 61% of the total electricity needed for upstream and midstream, which is similar to the range of 55%-60% registered for ECOPETROL, and this allows demonstrating that the installed capacity data of self-generation are congruent with the real capacities.

Figure B.7. Purchase and self-generation of electricity for upstream and midstream.

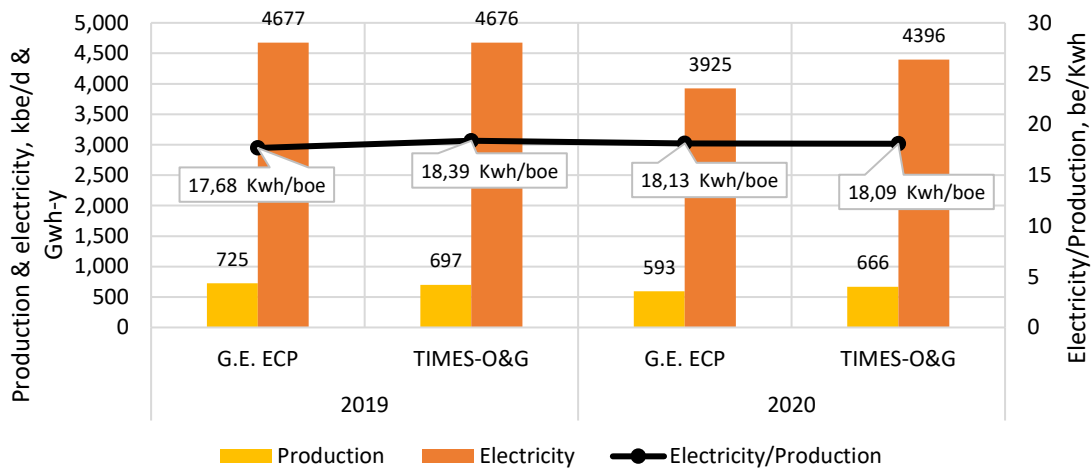


Note: The ECOPETROL data was taken from the Integrated Sustainable Management reports (ECOPETROL, 2019b, 2020, 2021b). The percentage of self-generation was calculated with respect to the total electricity used for the entire value chain, excluding the refinery because both in the model and in ECOPETROL the electricity from the refinery is self-generated.

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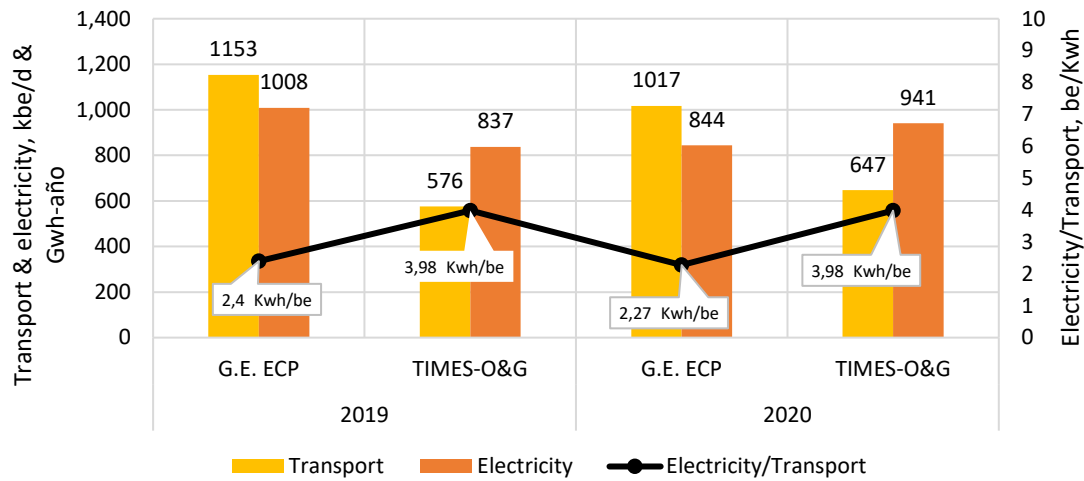
In addition, we wanted to compare the relationship between electricity consumed and hydrocarbon production (Figure B.8), and it was found that the difference between the TIMES-O&G model and historical data is 4.3% and 0.1% for the years 2019 and 2021 respectively. In the same way, the relationship between the electricity consumed and the fluids transported was calculated (Figure B.9), however, in this case it should be considered that: ECOPETROL does not have a direct operation in the transportation of natural gas, while the O&G company does; ECOPETROL accounts for the transportation of by-products through polyducts, while the TIMES-O&G model does not consider the transportation of these by-products. For the above reason, there are differences in electricity consumption between the historical data, but it is recalled that the transportation stage was simplified as it did not have relevant decarbonization routes compared to the production and refining stage (see annex 1, section 3.7).

Figure B.8. Electricity consumption in the production stage.



Data: The ECOPETROL data was taken from the Integrated Sustainable Management reports (ECOPETROL, 2019b, 2020): production data refers to the production of crude oil and natural gas (it does not include produced water) and the electricity consumed for this purpose. In the same way, the results of the TIMES-O&G model do. No information is reported for 2021 since the electricity consumption data for the production stage was not found.

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Figure B.9. Electricity consumption in the transportation stage.

Data: The ECOPETROL data was taken from the Integrated Sustainable Management reports (ECOPETROL, 2019b, 2020): the transport data refers to the fluids transported both by pipelines and polyducts and the electricity consumed for this purpose. The TIMES-O&G data presents the crude oil and natural gas that is transported (since the model does not represent the transport of derivatives).

B.3.2 Balance of crude oil

In Colombia, the demand for crude oil by the final consumption sectors is approximately zero. In the period 2006-2019, the industrial sector -the only one that demanded crude oil- consumed an average of 0.530 kb/d, which is equivalent to an average of 0.08% of national production of this period (UPME, 2022a). In addition, the demand estimate in the PEN update scenario -the only one in which the demand for crude oil for final use increases- shows that the demand for 2050 was a maximum of 0.538 kb/d, which represents 0.06% of the 2019 production.

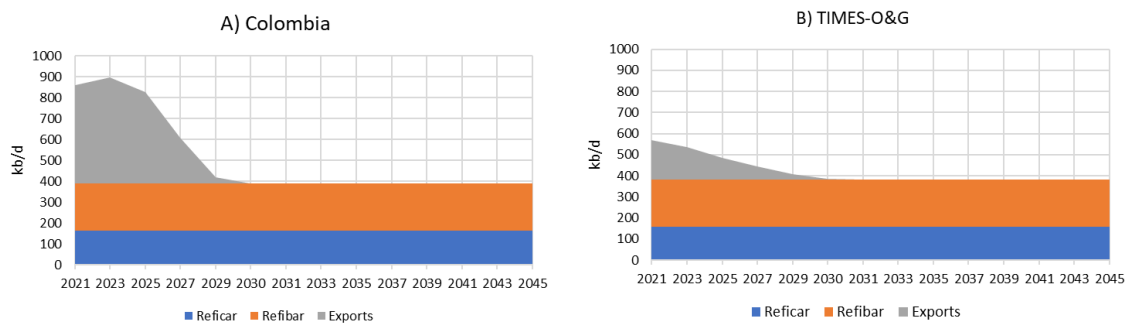
On the other hand, the main use of crude oil in Colombia is to supply the load of the two refineries, which are in charge of self-supplying the national demand for liquid fuels (UPME, 2021c). The surplus is exported and represents economic benefits for both Colombia and the exporting companies. In 2021 contributing 2.1% of the national GDP in 2021, with

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a participation of 12% of the nation's current income, and corresponding to 32% of total exports, especially crude oil (MINENERGIA et al., 2021).

Figure B.10 shows the loads to the refineries estimated up to 2045, in which it is observed that the refinery utilization factor of the refineries is the maximum assumed. In addition, the projections show that crude oil will be exported until 2030, while starting this year, crude oil production will be less than what is required by refineries. The difference between Figure B.10A and Figure B.10B is explained by the fact that the first refers to national production while the second refers to the O&G company's production.

Figure B.10. Oil crude load to refineries and export (regardless of type of crude)



Note: The data in graph A were taken from the UPME 2021 indicative liquid fuel supply plan, graph 4-12 (UPME, 2021c). data from the TIMES-O&G model presents gross oil exports.

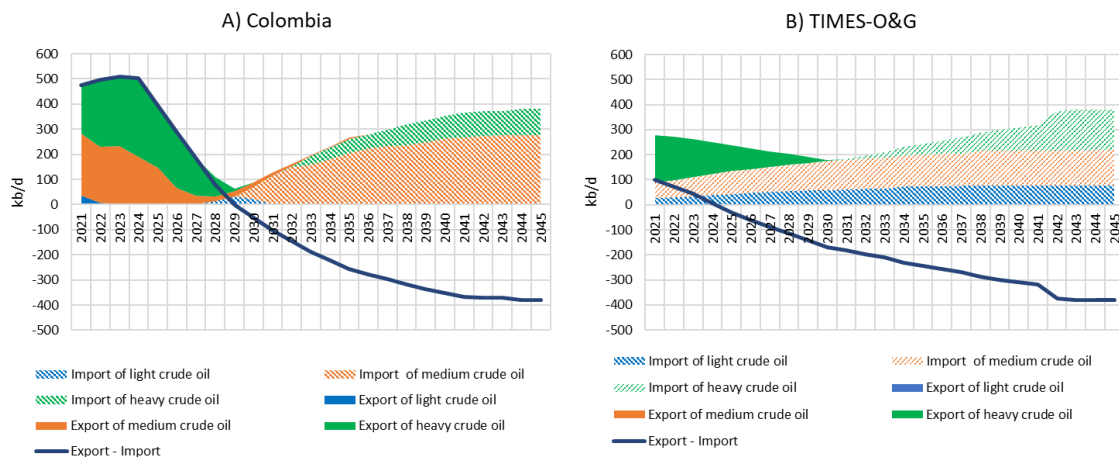
Figure B.11 shows the balance of exports and imports of crude oil according to its API gravity for Colombia and for the O&G company. In general, estimates for both Colombia and the O&G company show that by 2033 and 2032 around half of the crude oil -49.4% and 51.7% respectively- loaded to refineries will come from abroad; In the same way, from 2044 the total crude loaded to refineries will come from abroad, since from this date the production of both Colombia and the company will be almost zero (Figure B.2).

Regarding the balance for heavy crude oil, the projections for Colombia and the O&G company show that there will be a surplus for export -in different quantities due to the scope

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of production- until 2029 and 2030 respectively, after these dates, imports from abroad will begin to supply the demand to refineries for this type of crude. However, both models differ in the balance for medium and light crude, since projections for Colombia (Figure B.11A) show that refineries can be supplied with these type of crude until 2028 without resorting to imports from abroad, while the O&G company (Figure B.11B) must import light and medium crude from the 2021. It is important to clarify that the import process of the O&G company can be national -purchase of crude from other national producers- or international; note that from 2028 the import process can only be from other countries because Colombia will not have the capacity to load the refineries solely with national crude.

Figure B.11. Balance of import and export of crude oil according to quality.



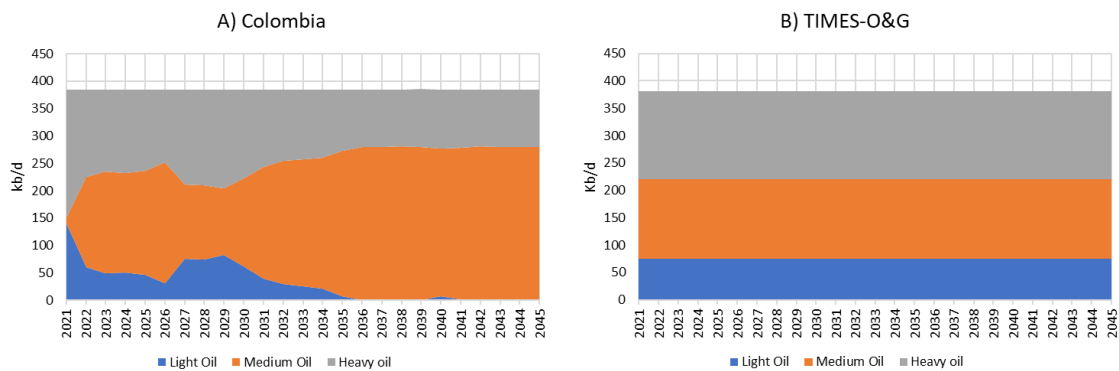
Note: The data in graph A were taken from the UPME 2021 indicative liquid fuel supply plan, graph 4-13 (UPME, 2021c).

The difference between the models in terms of the balances of medium and light crude is due to the demand of the refineries by type of crude, which is presented both for Colombia and for the O&G company in the Figure B.12. In the case of Colombia, the study carried out by UPME assumes a composition that varies over time -this composition is an assumption but not a result of this study, while in the case of the TIME-O&G model, it remains constant

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over time. For example, for the year 2021, the UPME study assumes that the demand for medium crude oil for refineries is of 11 kb/d, while in the TIMES-O&G model, refineries will demand 145 kb/d of this type of crude, then, if the model uses the same assumption as UPME, medium crude would not have to be imported this year, instead there would be a surplus of 30 kb/d for export²⁵. The TIMES-O&G model does not use the same assumption of the composition of the UPME, because the technical reasons for this assumption were not found; according to the UPME there are changes in the diets of the refineries, but no information was found on the change in the energy consumption of the refinery or in the consumption of hydrogen²⁶ as actually happens (Elgowainy et al., 2014; Ruth et al., 2020) .

Figure B.12. Load to Colombian refineries according to the type of crude.



Note: The data in graph A were taken from the UPME 2021 indicative liquid fuel supply plan, graphs 4-10 and 4-11 (UPME, 2021c). The load presented corresponds to the Barrancabermeja and Cartagena refineries in both cases.

B.3.3 Balance of natural gas

The natural gas balances for medium supply scenarios -without new discoveries-, the O&G company and Colombia agree that they will be able to supply the demand of

²⁵The production of light crude for 2021 by the O&G company is 48 kb/d (see **Error! Reference source not found.**), then assuming the load defined by UPME of 11 kb/d to the refinery (**Error! Reference source not found.**A), there would be an excess of 37 kb/d.

²⁶ In fact, the UPME liquid fuel supply plan does not present information on the required inputs to the refineries since it is not part of the scope and objective of this study (see **Error! Reference source not found.**).

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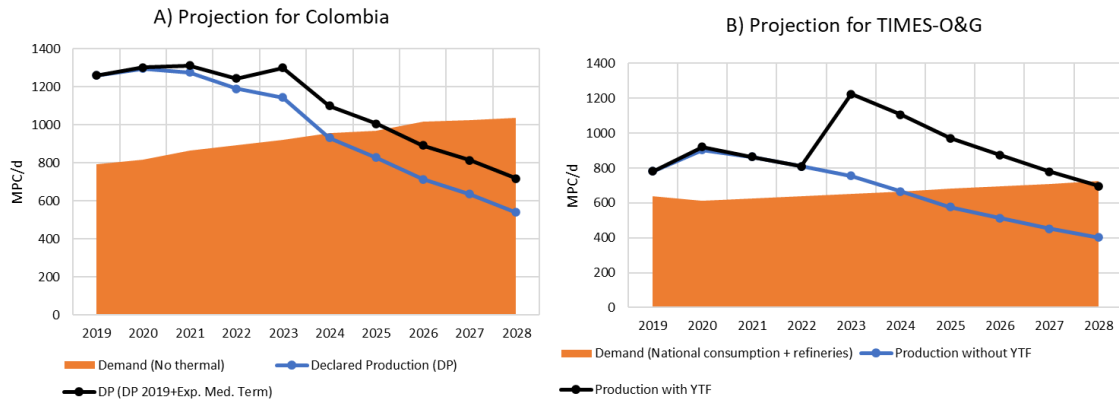
consumption sectors until 2024 and 2024 respectively (Figure B.13). After these dates, both the O&G company and Colombia must import natural gas internationally in amounts estimated at 319 MPC/d and 496 MPC/d respectively; The difference in the amount of natural gas that must be imported -also applies to the export surplus- in both estimates can be explained due to the differences in the production projection of both cases (analysis in section 4.1.2) and because the demand estimates for the Colombian case are calculated in the UPME technical plan for the supply of natural gas and are different from those assumed by the TIMES-O&G model that uses the PEN update scenario.

Although, before 2024 there is a surplus of natural gas in both cases, this does not necessarily imply an import abroad due to two reasons. First, in the Colombian case, the demand for thermoelectric plants that use natural gas to generate electricity was not taken into account because this demand was not considered in the TIMES-O&G model (see annex 1, section 2.2 and 2.3). In fact, if this demand and the presence of the El Niño phenomenon were taken into account, there would be supply problems in Colombia for 2021-2022. Second, there are other demands for internal consumption, for example for the company's self-generation processes of electricity.

Likewise, the medium supply scenario is presented with new discoveries, which allow self-sufficiency to be extended until 2025 and 2028 for Colombia and the O&G company respectively. Again, there are differences in the amount of natural gas imported after 2025, and it is due to the differences in the demand of both models, since the difference in production for 2028 from Colombia and from the O&G company is 22 MPC/D, but the difference in imported gas that year is 290 MPC/d. In both cases, a significant rebound in production is seen in 2023, which comes from medium-term exploration for Colombia and the exploitation of YTF resources in the TIMES-O&G model.

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Figure B.13. Balance of natural gas for Colombia and TIMES-O&G without YTF resources.



Note: Data for Colombia was taken from the UPME technical plan for the supply of natural gas 2020(UPME, 2020a), graph 3.1 and 3.2: the declared production and the non-thermal demand are presented (it does not include natural gas that is used for electricity generation). The TIMES-O&G projection presents production with and without considering new discoveries and demand for national consumption and refineries. Note that the demand estimates for the Colombian case are calculated in the UPME technical plan for the supply of natural gas and are different from those assumed by the TIMES-O&G model that uses the PEN update scenario.

B.3.4 Balance of refinery

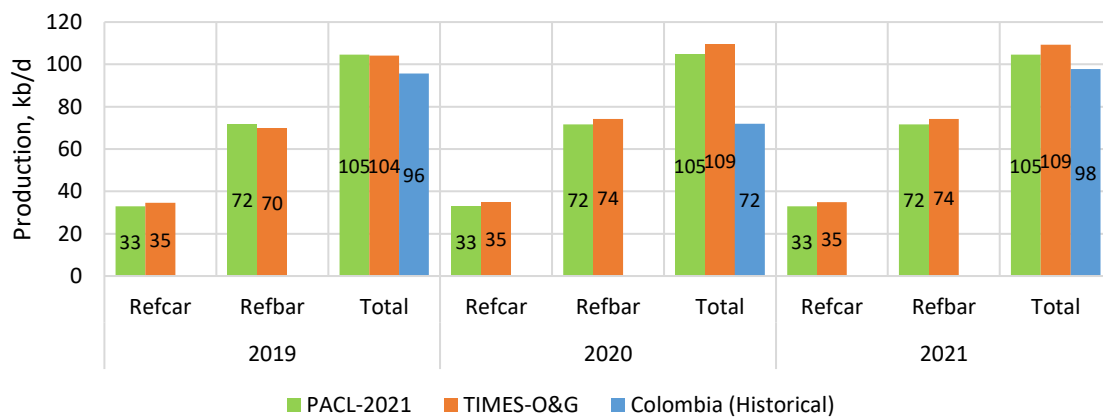
In the case of the refineries, the comparison between Colombia and the O&G company is direct, since the company operates the two refineries that supply the national market. Figure B.14 - Figure B.17 compare fuel production between three sources of information: projections from the TIMES-O&G model, which uses data from technical reports to establish the output composition of each of the refineries (see details in annex 1, section 4.4); the estimates of the UPME liquid fuel supply plan, which sets the constant volumetric production of each refinery throughout the time horizon; the historical data reported for Colombia at a general level.

In the case of gasoline and diesel, there are similarities between the production of each one of the refineries according to the UPME model and the TIMES-O&G model (see Figure B.14 and Figure B.15), which is a product of the fact that the use of the refinery is the maximum in both models (Figure B.10), and conversion to these products is similar. In the

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base year the estimate of the TIMES-O&G model has an error of only 8.3% and 7.4% for the historical production of gasoline and diesel respectively. However, in both projections - PACL-2021 and TIMES-O&G model- differences are observed with the historical data for the years 2020 and 2021. This is explained because the consumption of liquid fuels decreased in 2020 due to the pandemic and mobility restrictions and in 2021 the consumption of diesel and gasoline was barely reaching pre-pandemic levels(ACP, 2022). These aspects were not captured by the demand estimates of the models²⁷ and therefore they estimate growth for 2020 and 2021 in consumption of liquid fuels -which in turn drive the production of these fuels-, but that did not happen and therefore an overestimation of fuel production is observed.

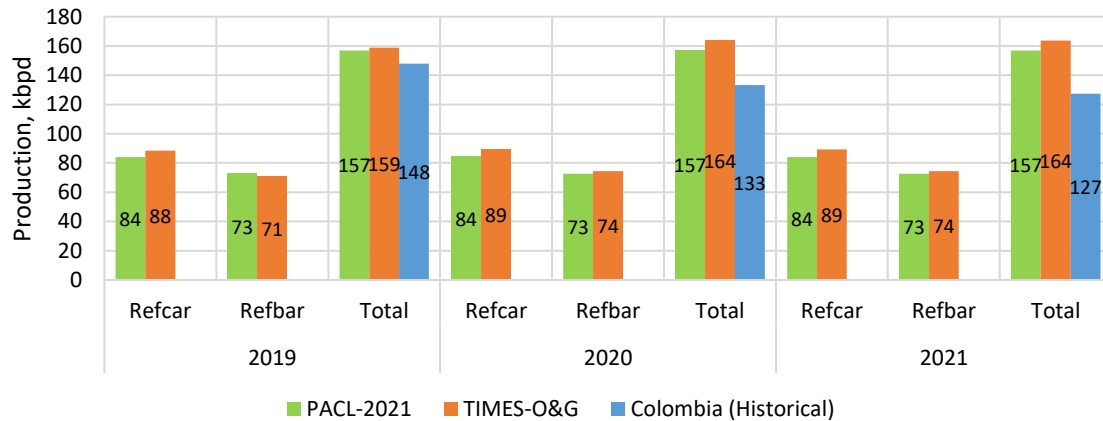
Figure B.14. Production of gasoline in each refinery.



Note: PACL-2021 refers to the production assumed by UPME in the indicative plan for the supply of liquid fuels 2021 (UPME, 2021c). The data for Colombia were taken from the report by the UPME statistical bulletin 2018-2022S1 (UPME, 2022b).

²⁷ Many of them were made before or during the pandemic.

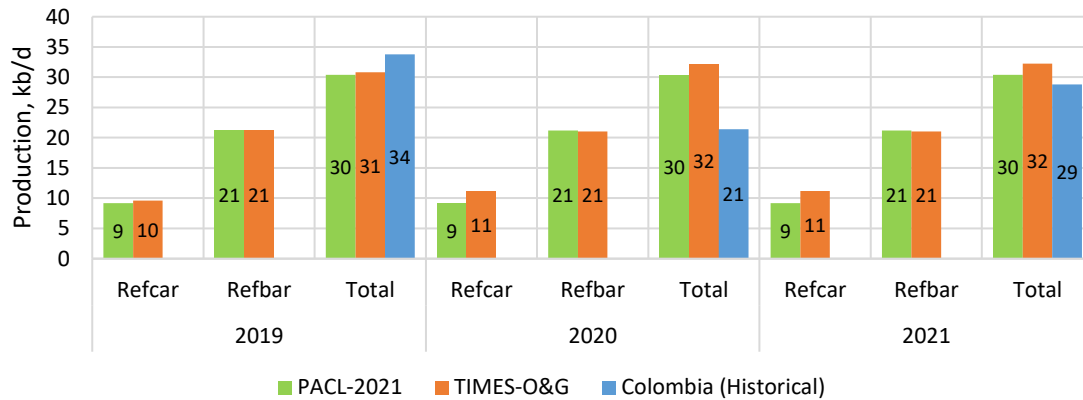
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Figure B.15. Production of diesel in each refinery.

Note: PACL-2021 refers to the production assumed by UPME in the indicative plan for the supply of liquid fuels 2021 (UPME, 2021c). The data for Colombia were taken from the report by the UPME statistical bulletin 2018-2022S1 (UPME, 2022b).

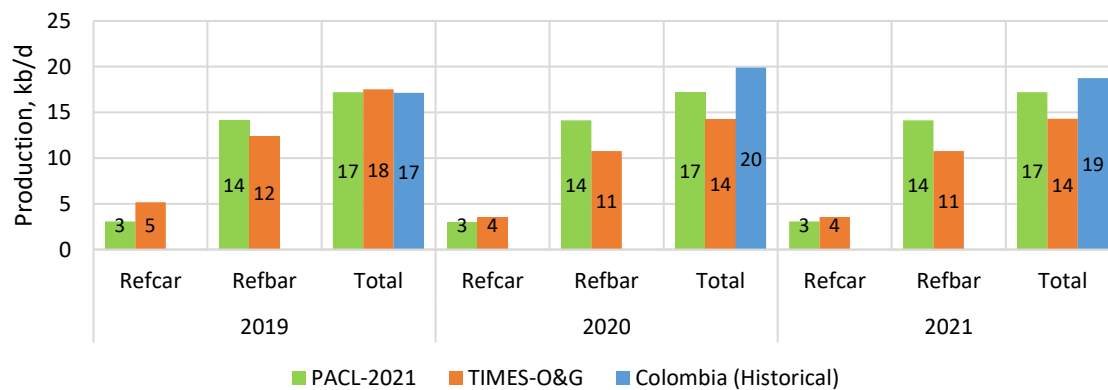
The pandemic also affected the consumption of kerosene (ACP, 2022), and therefore the same behavior observed for gasoline and diesel is observed in kerosene production from refineries (Figure B.16). In this case, the errors calculated for the TIMES-O&G model with respect to the historical series are 8.8% and 10.3% for the years 2019 and 2021. It should also be noted that the production in the Barrancabermeja refinery is the same for the TIMES-O&G model and the model carried out by UPME, and in the case of the Cartagena refinery, the difference is a maximum of 2 kb/d.

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Figure B.16. Kerosene production in each refinery.

Note: PACL-2021 refers to the production assumed by UPME in the indicative plan for the supply of liquid fuels 2021 (UPME, 2021c). The data for Colombia were taken from the report by the UPME statistical bulletin 2018-2022S1 (UPME, 2022b).

On the contrary, in the case of LPG, consumption during the pandemic was maintained, and even presented an increase of 5% compared to 2019, especially in the residential sector, driven by the quarantine (GASNOVA, 2021). Since the UPME and TIMES-O&G models do not consider these effects, the demand and production of LPG are underestimated. Then, the error calculated for the TIMES-O&G model with respect to historical data is 5.8%, 30% and 26.3% for the years 2019, 2020 and 2021 respectively.

Figure B.17. LPG production in each refinery.

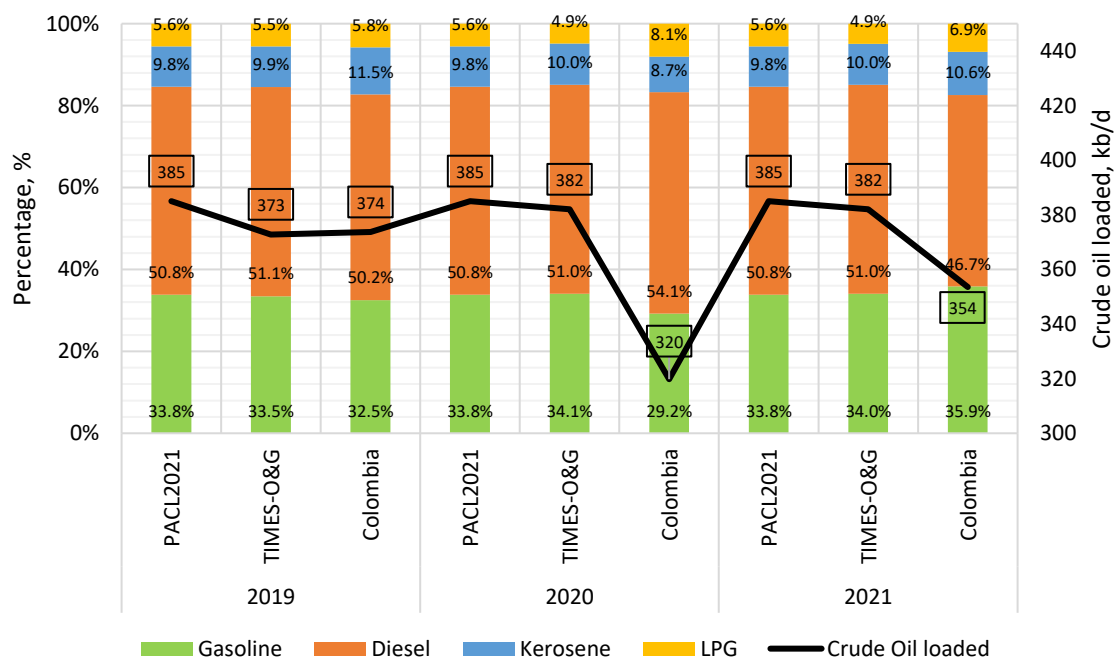
Note: PACL-2021 refers to the production assumed by UPME in the indicative plan for the supply of liquid fuels 2021 (UPME, 2021c); In the case of the Barrancabermeja refinery (refine) the production from the fields is added, which is

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why this is also done to report the TIMES-O&G data in this graph. The data for Colombia were taken from the report by the UPME statistical bulletin 2018-2022S1 (UPME, 2022b).

Despite the differences in observed fuel productions (Figure B.14 - Figure B.17) and the amount of crude loaded to the refineries, the composition of the light product refinery outputs is similar between the models and the historical data are similar (Figure B.18), the main differences are observed for the year 2020, where historical data estimates 54.1% and 8.1% of diesel and LPG production over total products compared to 51.0% and 4.9% of the TIMES-O&G model, respectively. This implies that in general, the production of fuels from refineries of the TIMES-O&G is consistent with historical data and the UPME model.

Figure B.18. Composition of refineries in Colombia



Note: The composition was calculated based on gasoline, diesel, kerosene, and LPG based on data of the **Error! Reference source not found.** For this calculation, other products considered in the TIMES-O&G model such as fuel oil, refinery gas and avigas were not included because there are no data to be compared.

B.3.5 Balance of fossil fuels

The UPME has developed studies whose objective is to analyze in detail the self-sufficiency of liquid fuels, natural gas and LPG (UPME, 2018c, 2020a, 2021c). Each of these

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studies focuses solely on the commodity of interest, analyzes supply, transportation, and demand. However, the assumptions for each report differ from each other, and do not take into account the interactions that could occur between commodities²⁸ or different scenarios²⁹. In contrast, the TIMES-O&G model makes it possible to establish the balance between the supply and demand of each commodity within a system and under different scenarios³⁰, but it does not detail its transportation facilities. Despite this, it is sought that the TIMES-O&G model not only correctly represents fuel production (sections 4.2-4.4), but also allows representing fuel balances in Colombia.

B.3.5.1 Gasoline

In the case of gasoline, both the UPME report and the TIMES-O&G model show the need for imports to meet national demand throughout the analysis period (Figure B.19). The main difference is the year 2021, where the import of gasoline with respect to national production is 3% and 16% according to the UPME and the TIMES-O&G model respectively; the differences in the quantity imported are mainly explained by the differences in the demand stipulated for each study, which vary between 108 - 144 kb/d and 126-145 kb/d in the UPME report and the TIMES-O&G model respectively. In both cases, the import of gasoline with respect to national production can represent up to 37% and 33% according to the UPME and the TIMES-O&G model respectively.

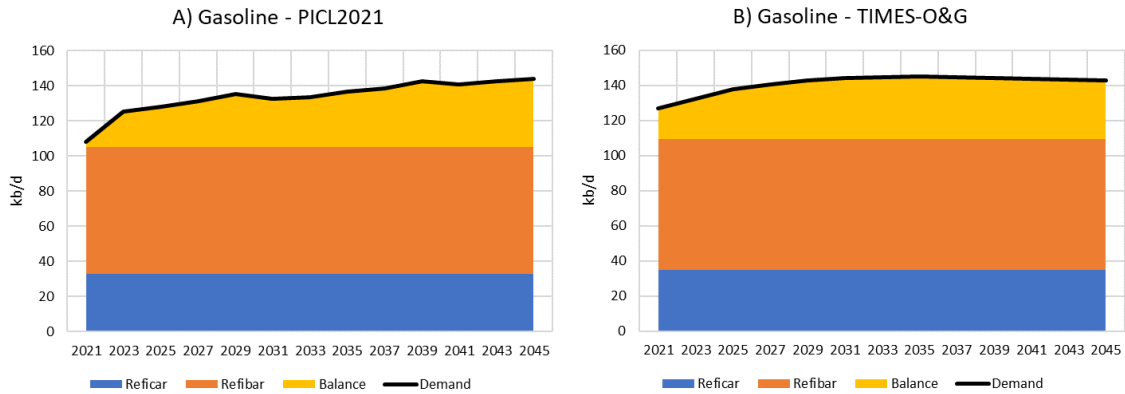
²⁸ For example, the technical study for liquid fuels assumes that refineries can operate at high utilization factors in the long term (at least until 2045), without taking into account their natural gas consumption(UPME, 2021c). On the other hand, the technical study for natural gas shows supply problems in the short and medium term (before 2028 in any case)(UPME, 2020a).

²⁹ In the case of natural gas, the UPME presents the balances only with the average demand scenario; in the case of LPG, the report establishes the demand with the base scenario of the demand projection; in the case of liquid fuels, it only presents a demand scenario that in turn is used to carry out the balances.

³⁰ For the validation process, the balances are presented taking into account the base demand scenario that corresponds to the PEN update scenario (more detail in annex 1, section 2.3).

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Figure B.19. Comparison of long-term projections for the gasoline balance.

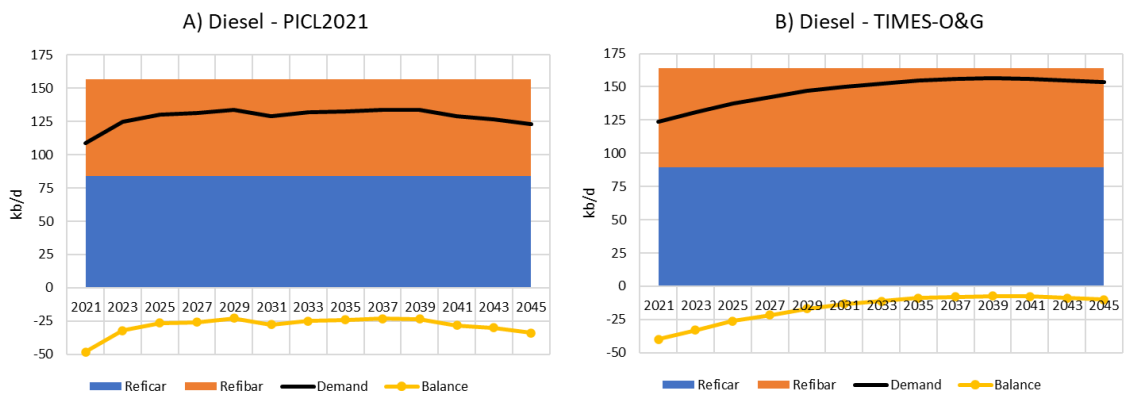


Note: The data in graph A were taken from the UPME 2021 indicative liquid fuel supply plan, graph 4-14 (UPME, 2021c). The balance represents demand minus supply, then a positive value represents an import, while a negative value represents an export.

B.3.5.2 Diesel

Contrary to gasoline, the national production of diesel manages to supply the national demand during the entire period of analysis, and even allows the export of this fuel estimated on average of 18% and 10% according to the UPME report and the TIMES-O&G model respectively (Figure B.20). Once again, there are differences in the demand for diesel, which can reach values of 156 kb/d according to the TIMES-O&G model, and which are 16.8% higher than the maximum demand in the UPME report -which is stipulated at 134 kb/d-.

Figure B.20. Comparison of long-term projections for the diesel balance



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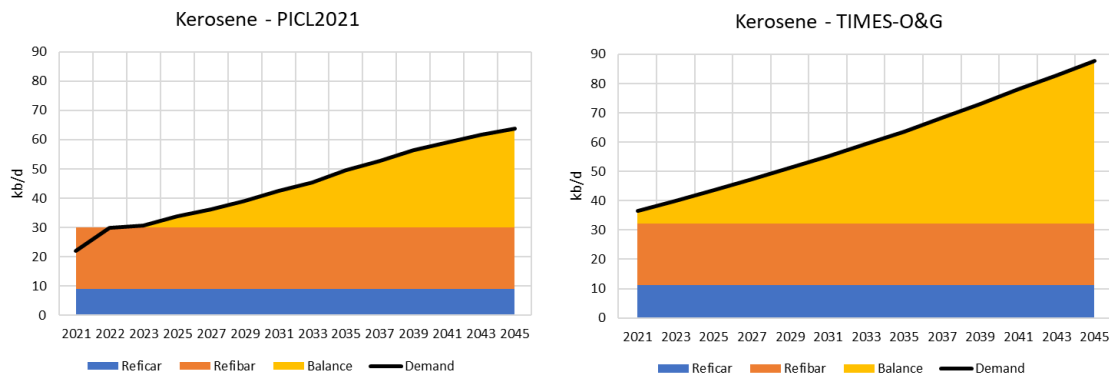
Note: The data in graph A were taken from the UPME 2021 indicative liquid fuel supply plan, graph 4-15 (UPME, 2021c). The balance represents demand minus supply, then a positive value represents an import, while a negative value represents an export.

B.3.5.3 Kerosene

The balances for kerosene from UPME and the TIMES-O&G model differ mainly in the projected demand, because in the former the consumption in 2045 would reach values of 64 kb/d while in the latter the demand would be up to 87 kb/d. For this reason, the amount imported would be equal to or greater than national production from 2041 and 2035, according to the UPME report and the TIMES-O&G model, respectively.

However, if we take into account not the update scenario for the TIMES-O&G model, but the upgrading scenario, we would have similar results in the balance and in the magnitude of fuel imports, since this scenario assumes that consumption will be 61 kb/d by 2045, which only differs by 3% from the estimated demand in the UPME report.

Figure B.21. Comparison of long-term projections for the kerosene balance



Note: The data in graph A were taken from the UPME 2021 indicative liquid fuel supply plan, graph 4-16(UPME, 2021c). The balance represents demand minus supply, then a positive value represents an import, while a negative value represents an export.

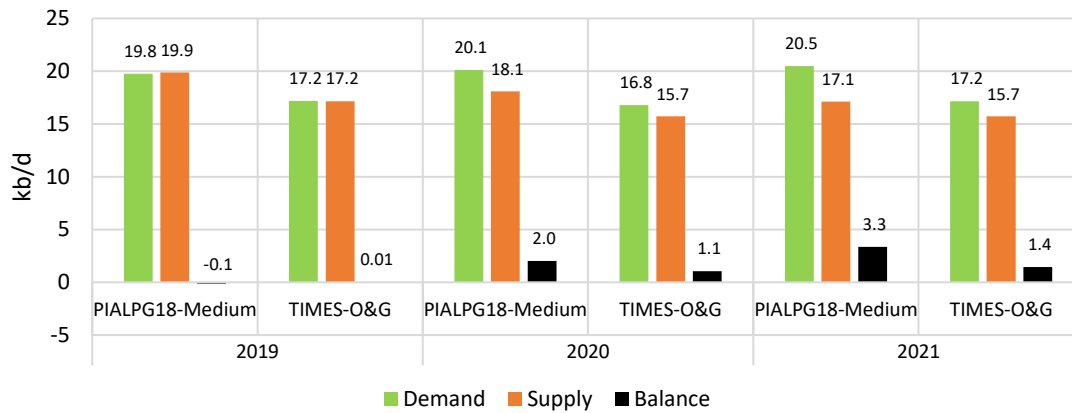
B.3.5.4 LPG

In the case of LPG, there are balances in the short, medium (UPME, 2018c) and long term (UPME, 2021c) to compare them with the TIMES-O&G. In the short term, it can be

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seen that both the UPME and the TIMES-O&G model predict the need for imports to meet demand under scenarios of medium LPG supply (Figure B.22), while if a high supply scenario is considered, both models predict that there would be a surplus for export (Figure B.23). The difference in the amounts of export and import between both models is due to two aspects: the first is related to the projection of demand, which is underestimated by the TIMES-O&G model compared to the UPME report; For the base year, the production of other actors -different from Ecopetrol- represented 15.07% of the national production, and it is estimated that by 2022 they would still participate in 5.16%(UPME, 2018c), however, the supply of these producers was not considered in the model TIMES-O&G, then the national production is not represented in its entirety.

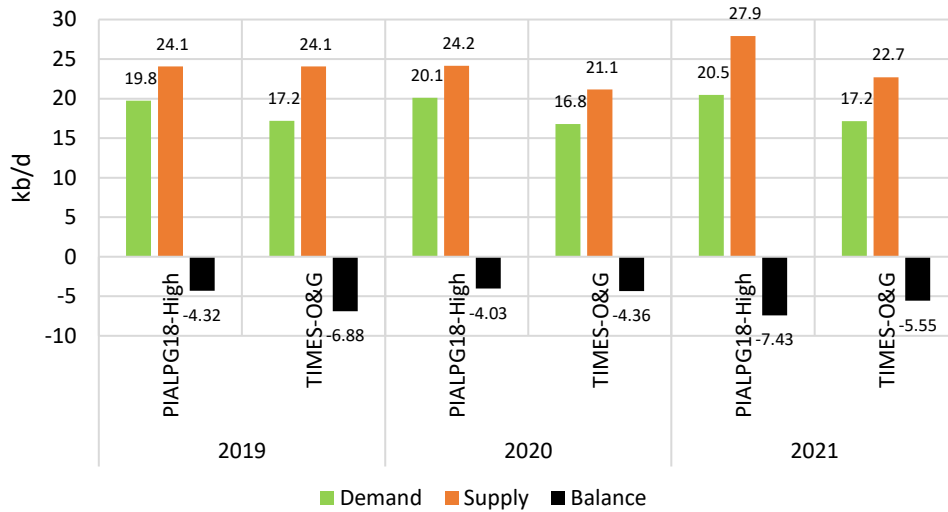
Figure B.22. Comparison of short-term projections for the LPG balance using medium supply scenario.



Note: The PIALPG18-Medium data refer to the declared production for Colombia (it does not include the Cupiagua processing plant project) according to the UPME indicative LPG supply plan in 2018, graph 33 (UPME, 2018c). The data for TIMES-O&G presents production by both refineries and oilfields without considering the Cupiagua processing plant project.

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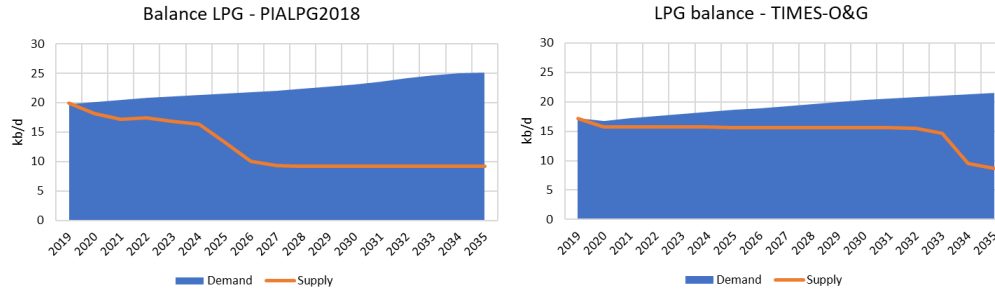
Figure B.23. Comparison of short-term projections for the LPG balance using high supply scenario.



Note: The PIALPG18-High data refer to the declared production for Colombia (it includes the Cupiagua processing plant project and the continuation of the plant in Floreña oilfield) according to the UPME indicative LPG supply plan in 2018, graph 33 (UPME, 2018c). The data for TIMES-O&G presents production by both refineries and oilfields with considering the Cupiagua processing plant project.

In the case of the medium-term balance, both models forecast the deficit from 2020, requiring importation to meet national demand (Figure B.24). In this case, the differences in the amounts imported are not only represented by the differences in demand -variations of 15% for 2035-, but also by the projected production, since in the case of the UPME report it assumes a decline until 2027 followed by constant production of approximately 9 kb/d, while in the case of the TIMES-O&G model it remains approximately constant until 2034 at 15 kb/d.

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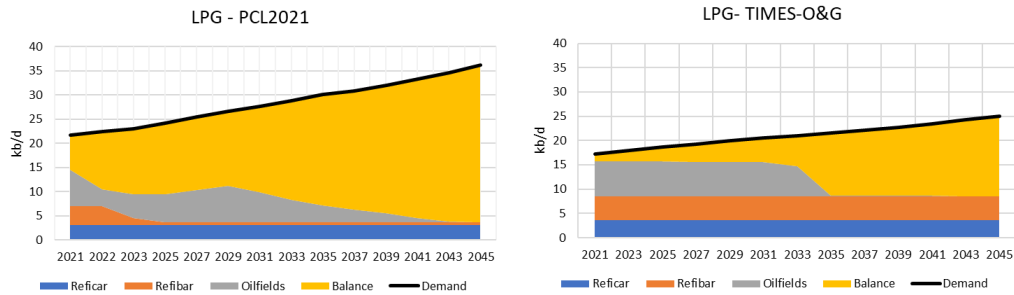
Figure B.24. Comparison of medium-term projections for the LPG balance

Note: The PIALPG18 data refer to the declared production for Colombia (it does not include the Cupiagua processing plant project) according to the UPME indicative LPG supply plan in 2018, graph 31 (UPME, 2018c). The data for TIMES-O&G presents production by both refineries and oilfields without considering the Cupiagua processing plant project.

The comparison of the long-term estimates (Figure B.25) shows similarities with the medium-term (Figure B.24) ones³¹, and also allows explaining the differences in the LPG supply. According to the UPME, the production of the Barrancabermeja refinery decreases from 4.0 kb/d to 0.7 kb/d in 2022 -the report does not detail the cause of this decrease-, while in the TIMES-O&G model, the production of LPG from this refinery remains constant. On the other hand, in the TIMES-O&G model, the transformation of natural gas to LPG in oilfields is prioritized because it supposes an increase in the commercial value of natural gas and LPG -the prices of these two commodities have a relation of 3.68 for the base year and that can be up to 4.80 in 2050-, then LPG production remains constant until 2033, year in which the production of natural gas from the fields where the transformation centers exist is not enough to be taken to these facilities; On the other hand, according to the UPME, the production from the fields varies with time, and by 2033 the production is 4.6 kb/d, and it does not drop to zero until the year 2045.

³¹ It should be noted that the medium-term estimates are presented in the UPME report that only analyzes the LPG context(UPME, 2018c), while the long-term estimates arise from the UPME report that analyzes liquid fuels in general (UPME, 2021c).

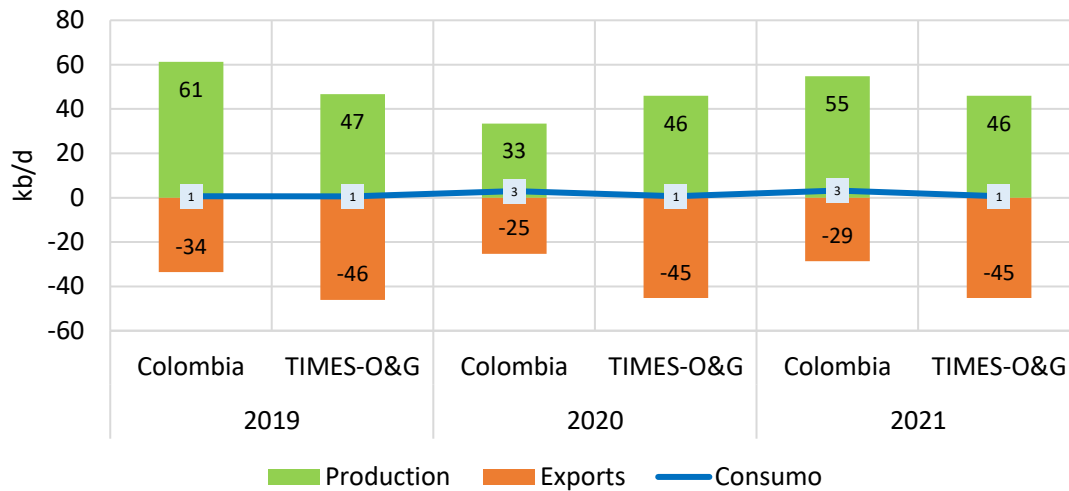
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Figure B.25. Comparison of long-term projections for the LPG balance

Note: The data in graph A were taken from the UPME 2021 indicative liquid fuel supply plan, graph 4-17 (UPME, 2021c). The balance represents demand minus supply, then a positive value represents an import, while a negative value represents an export.

B.3.5.5 Fuel Oil

Figure B.26 compares the balances of the TIMES-O&G model with historical data, since no projections or balances were found that could be used for this validation process. Despite the possible influence of the pandemic, the demand of the consumption sectors of the TIMES-O&G model is similar to historical data, and in any case, they represent an average of 5.2% of national production -with a maximum of 8.72%. which occurs in 2020 when production is lower than in other years due to low refining activity-. Although the TIMES-O&G model replicates the self-sufficiency of this fuel for Colombia, it overestimates the amount exportable abroad compared to historical data, however, these differences may occur due to inconsistencies in fuel oil inventories: according to BECO , there is an error in the fuel oil balance of 97.7%, 63.1%, and 87.6% for the years 2019, 2020, 2021, respectively, which may be due either to the production or export of fuel oil.

Figure B.26. Comparison of the fuel oil balance with historical data

Note: The data for Colombia were taken from the BECO (UPME, 2022a): import minus export data are presented, with a positive value representing a net import while a negative value represents a net export. The results of the TIMES-O&G model were presented under the same consideration.

B.3.6 Emissions

There are no projections of emissions from the hydrocarbons sector in Colombia with which the TIMES-O&G model can be compared. Of the studies cited for validation (Table B.1), the only study that takes emissions into account is the national energy plan (PEN), but the latter only takes into account emissions from fuel consumption in the "agriculture, construction and mining" sector, therefore it is not possible to know in detail what the hydrocarbon sector emissions would be. Then, the estimated emissions from the TIMES-O&G model are compared only with historical data from the reference company.

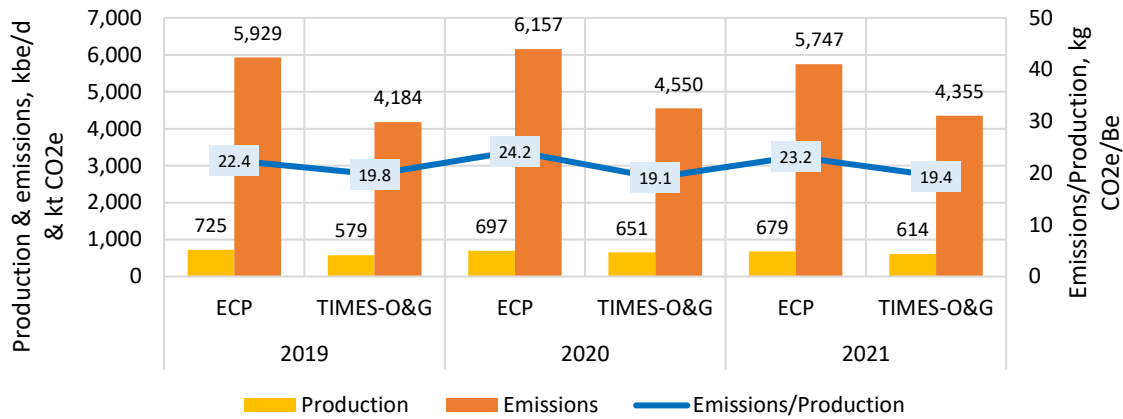
B.3.6.1 Emissions in production and transportation stage

The relationship between the emission of greenhouse gases per unit of hydrocarbons produced or refined makes it possible to compare Ecopetrol's historical data with the

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estimates of the TIMES-O&G model. In the case of oil and natural gas production, errors of 12%, 21% and 16% were obtained for the years 2019, 2021 and 2022 respectively.

Figure B.27. Emission (scope 1+2) from production and transportation stage..

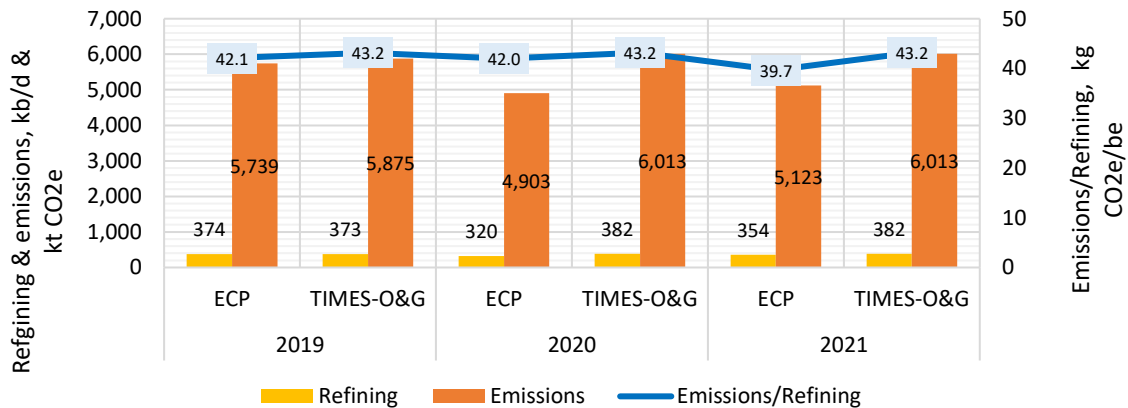


Note: Production includes both natural gas and oil, expressed in barrels of equivalent and data was taken from the Integrated Sustainable Management reports of the company (ECOPETROL, 2019b, 2020, 2021b), while the emissions were taken from the company's 2018-2021 GHG inventory (ECOPETROL, 2021a).

B.3.6.2 Emissions in refining stage

Likewise, the charge to the refineries was compared with the emissions associated with the process, and errors of 3%, 3% and 9% were found. However, it should be noted that, unless decarbonization pathways are added, refinery emissions according to the TIMES-O&G model will remain constant if the load on refineries does as well -behavior evidenced up to 2050 (Figure B.10)- because there is no there is flexibility in fuel inputs to the refinery (see annex 1, section 4.1).

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Figure B.28. Emissions (scope 1+2) from refinery stage

Note: refining refers to the amount of crude loaded into refineries and data was taken from the Integrated Sustainable Management reports of the company (ECOPETROL, 2019b, 2020, 2021b), while the emissions were taken from the company's 2018-2021 GHG inventory (ECOPETROL, 2021a).

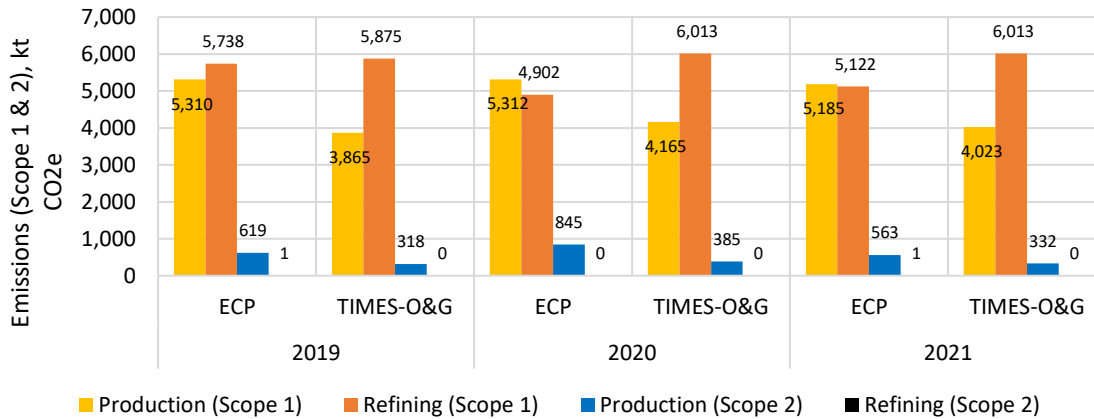
B.3.6.3 Emissions per stages

Likewise, the TIMES-O&G model allows differentiating emissions by scope and by stage and the results shows an appreciable difference in the ratio of production and refining emissions (Figure B.29). The share of emissions from the refining process represents between 44.3% and 49.1% of Ecopetrol's total, while according to the TIMES-O&G model, this relationship varies between 56.9% and 58.4%. This difference is explained by two reasons: despite the fact that the relationship between emissions and crude oil load is similar for both Ecopetrol and the TIMES-O&G model (Figure B.28), the magnitude of emissions from refining in the TIMES-O&G model overestimates the Ecopetrol emissions due to higher crude oil load in the model (Figure B.28); beside, emissions from production estimated by the TIMES-O&G model are lower than those of Ecopetrol because the model does not represent the total production of Ecopetrol and the relationship between production and emissions is underestimated by the model compared to that calculated for Ecopetrol (Figure B.27).

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Despite the above, in both stages the TIMES-O&G model replicates that scope 1 emissions predominate over scope 2; if the share of scope 1 emissions is calculated in relation to scope 1 + scope 2 emissions, it is found that this relationship varies between 92-95% and 96-97% for Ecopetrol and the TIMES-O&G model respectively.

Figure B.29. Emissions by stage and scope.



Note: Emissions data were taken from the company's 2018-2021 GHG inventory (ECOPETROL, 2021a).

B.3.6.4 Emissions per scope

The figure consolidates the emissions of the O&G company according to scopes 1, 2 and 3. The differences of scopes 1 estimated by the TIMES-O&G model have errors of 11.8%, 0.4% and 2.60% for the years 2019, 2020, and 2021 respectively, but the differences in the magnitude of emissions in the production and refining stages mentioned above must be taken into account.

Regarding scope 2, which relates emissions from purchases to the national grid, significant errors of 48.7%, 54.5% and 41% are obtained for the years 2019, 2020, and 2021 respectively. This occurs because the TIMES-O&G model uses a constant emission factor for the national grid of 0.176 kg CO₂-eq/Kwh (see annex 1, section 2.2, table 3), while the

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emission factor does vary for Ecopetrol and is 0.269, 0.348 and 0.243 kg CO₂-eq/Kwh³². It should be noted that scope 2 emissions basically correspond to the production and transportation stages (Figure B.29), then if the TIMES-O&G model correctly estimated the emissions of this scope -using the same emission factors calculated for Ecopetrol-, it would have higher emissions in the production stage and therefore the relationship between emissions and production would increase and the error calculated respect to historical data in section **B.3.6.1 Emissions in production and transportation stage** would decrease.

Concerning the scope 3, errors of 31%, 21%, and 22% are obtained for the years 2019, 2020, and 2021 respectively. For this scope, the following should be considered: Ecopetrol takes into account the sale of products -this represented 94.89% of the total scope 3 in 2021(ECOPETROL, 2021a)-, the acquisition of goods and services, and investments, while the TIMES-O&G model does not take these last two into account; there may be products that are sold by Ecopetrol and are not considered in the TIMES-O&G model, such as naphtha; scope 3 quantification by Ecopetrol follows the ISO 14064-1 and GHG Protocol methodologies (ECOPETROL, 2021a), while scope 3 quantified by the TIMES-O&G model is a simplification that uses fuel emission factors without distinguishing the use in different sectors or if they are exported.

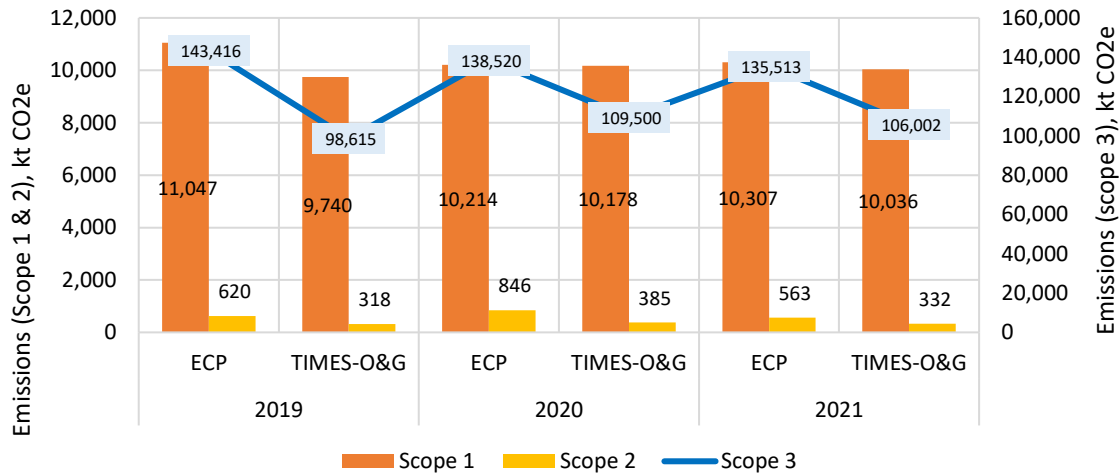
Despite this, the TIMES-O&G model manages to replicate the relationships between scopes, since scope 1 represents between 8.5% and 8.9% of total emissions, a range close to what Ecopetrol stipulates, which varies between 6.8% and 7.1%. The same occurs with scope

³² This emission factor was calculated as the ratio of Scope 2 emissions in all stages of Ecopetrol (**Error! Reference source not found.**) and purchases of electricity from the national grid (**Error! Reference source not found.**) (ECOPETROL, 2019b, 2020, 2021a, 2021b).

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2, which represents between 0.30-0.34% and 0.38-0.57% of total emissions according to the TIMES-O&G model and Ecopetrol respectively.

Figure B.30. Emissions per scope.



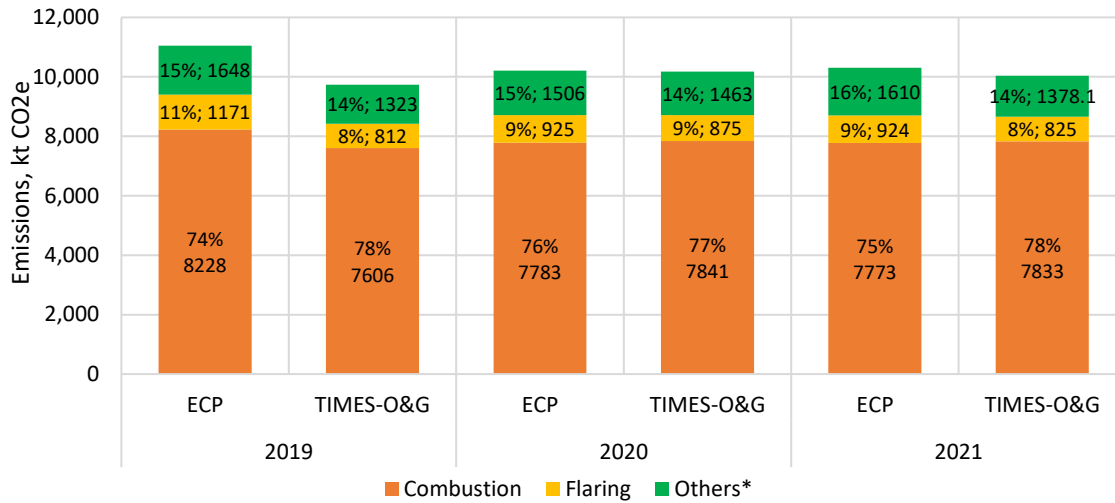
Note: Emissions data were taken from the company's 2018-2021 GHG inventory (ECOPETROL, 2021a).

B.3.6.5 Emissions per source

Ecopetrol's inventory distinguishes emissions by sources: combustion, mobile, flaring, and venting. On the other hand, the TIMES-O&G model accounts for the following sources (more detail in annex I, section 2.5): emissions that imply the combustion of fuels for different uses; the flaring of natural gas in production; other emissions established by activity emission factors -taken from a study that analyzed Ecopetrol's value chain (E. Yáñez et al., 2018)- and therefore the source is not exactly established.

The TIMES-O&G model allows replicating that the main source of emissions is combustion, which represents between 77% and 78% of total emissions, a range that is similar to that established by Ecopetrol of 74% and 77%. Regarding emissions from flaring, it can be seen that they continue to represent 8-9% and between 9-11% of total emissions according to the TIMES-O&G model and Ecopetrol, respectively.

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Figure B.31. Emissions per source in scope 1 + scope 2.

Note: Emissions data were taken from the company's 2018-2021 GHG inventory (ECOPETROL, 2021a). In the case of ECP, others refer to the sum of fugitives, mobiles and vents.

Appendix C: Documentation for the disruptive scenario in TIMES-O&G

C.1 Renewable energy

The processes of the production stage require electricity, which can be purchased from the national grid or self-generated on site. There is no detailed information for each field or the reference company, therefore, the UPME 2014 self-generation and cogeneration inventory was used (UPME, 2014). This study distinguishing between the production and transportation stage, but does not detail in the data for ECOPETROL, then, it was decided to assume the following: since ECOPETROL controlled 57% of the production of the companies reported in the study, it was assumed that the installed capacity of the reference company is 57% of the total reported; In order to know the installed capacity of each sedimentary basin, the data reported from each department was related to each sedimentary basin -e.g.: the data reported for the department of Meta were assumed for the Llanos

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Orientales basin-. In this way, the inventory of the installed self-generation capacity for the model is stipulated as shown in Table C.1.

Table C.1. Installed capacity for self-generation in each sedimentary basin.

Oilfield	Production stage (MW)				Transport stage (MW)		
	LPG	Natural Gas	Crude Oil	Diesel	Natural Gas	Crude Oil	Diesel
CAM1	0	34,25	0	0	14,78	0	0
CAM2	20,0	150,1	0	11,4	3,62	0	13,57
CAM3	0	131,9	48,3	11,4	0	14,48	13,57
CAM4	0	0	21,2	10,03	0,47	1,88	3,52
CAM5	0	19,45	41,4	19,6	1,21	4,83	9,05
CAM6	0	2,3	19,7	9,3	0,47	1,88	3,52
CAM7	0	0,3	0	8,9	0,13	0,54	1,01

Note: Adapted from UPME (UPME, 2014).

According to the UPME self-generation inventory, the main type of technology for generation based on natural gas is combustion turbines and internal combustion engines for liquid fuels(UPME, 2014). Based on this, the parameters of the installed self-generation technologies are reported in Table C.2. The economic parameters (CAPEX, FIXOM and VAROM) of natural gas were taken from the Annual Technology Baseline for Electricity developed by NREL (NREL, 2021), assuming the "Gas-CT" technology in the moderate scenario, while data of liquid-based generation, The Palgrave Handbook of International Energy Economics with diesel-based technology was used (Farnossh, 2021). According to the NREL, the useful life of these technologies is 30 years (NREL, n.d.); however, the date of installation is unknown, so it will be assumed that they were all installed in 2003, the year in which the UPME mentions that there was a significant increase in self-generation capacity in the oil sector (UPME, 2014); In this way, if the base year is 2019, all the technologies

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would have a remaining useful life of 13 years. Finally, the efficiency data were taken as the average of the efficiencies reported in the LEAP model for self-generation in the period 2010-2019 (Das et al., 2020), and all installed self-generation technologies assumed an average maximum utilization factor of 75%, as already used by a study for the national grid (E. Yáñez et al., 2020b).

Table C.2. Parameters for existing capacity of the self-generation based on fossil fuels.

Process	EFF	CAPEX	FIXOM	VAROM	LIFE
	%	USD/KW	USD/KW	USD/KWh	years
Based on Natural Gas (CT)	37.6%	936	21	0.00495	13
Based on Crude oil	35.8%	1150	20	0.014	13
Based on Diesel	35.6%	1150	20	0.014	13
Based on LPG	35.9%	-	20	0.014	13

Note: EFF refers to efficiency, FIXOM refers to fixed operation and maintenance expenses and VAROM refers to variable operation and maintenance expenses; LIFE refers to useful life. Data taken according to what was mentioned in the previous paragraph.

The foregoing implies that no later than 2032, investment must be made in new self-generation capacities to continue feeding hydrocarbon production with electricity -if it is optimal compared to buying directly from the national grid-. In fact, it is assumed that CAM8 -the oilfield that represents new discoveries- it is assumed that there are no installed capacities, then in 2023 investment in new capacities must be made. Then, thermal, and renewable technologies are proposed, with three levels of development every 10 years starting in 2020. Data for natural gas, solar and wind energy generation was based on the Annual Technology Baseline for Electricity developed by NREL, which presents three projection scenarios (conservative, moderate, advanced) (NREL, n.d., 2019); natural gas data is distinguished between combined cycle (CC) and combined cycle with capture carbon

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sequestration (CC-CCS) technologies. In addition, the steam turbine fuel oil Conventional technology was included, taking data from the PRIMES model-18, since fuel oil is a fuel considered in this study with an available factor of 35% (Capros & Evangelopoulou, 2018). The diesel and crude oil-based technologies cited in Table C.3 were also available.

Table C.3. Techno-economics parameter for new generation technologies under different scenarios.

Scenario	PROCESS	Year	CAPEX,	FIXOM,	VAROM,	EFF, %	LIFE, year
			USD/Kw	USD/Kw	USD/MWh		
Moderate	-	2020	1332	23	3,1	35%	40
		2020	1049	27	1,7	53,6%	30
	GAS-CC	2030	999	27	1,7	53,6%	30
		2040	955	27	1,7	53,6%	30
	GAS-CC-CCS	2020	2571	65	5,7	47,7%	30
		2030	2167	63	5,6	50,2%	30
		2040	1879	60	5,3	55,3%	30
	Solar - Utility PV	2020	1378	23	0	100%	30
		2030	776	17	0	100%	30
		2040	707	16	0	100%	30
	Land-based Wind	2020	1392	43	0	100%	30
		2030	950	39	0	100%	30
		2040	855	36	0	100%	30
	Advanced	GAS-CC	2020	1049	27	2	53,6%
2030			999	27	2	53,6%	30
2040			955	27	1,7	53,6%	30
GAS-CC-CCS		2020	2490	65	6	47,7%	30

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	2030	1866	62	5	53,0%	30
	2040	1496	56	5	65,9%	30
	2020	1378	23	0	100%	30
Solar - Utility PV	2030	638	15	0	100%	30
	2040	559	14	0	100%	30
	2020	1369	42	0	100%	30
Land-based Wind	2030	700	34	0	100%	30
	2040	613	29	0	100%	30
	2020	1049	27	2	53,6%	30
GAS-CC	2030	999	27	2	53,6%	30
	2040	955	27	1,7	53,6%	30
	2020	2652	65	6	47,7%	30
GAS-CC-CCS	2030	2466	65	6	47,7%	30
	2040	2263	65	6	47,7%	30
Conservative	2020	1378	23	0	100%	30
Solar - Utility PV	2030	1182	21	0	100%	30
	2040	979	19	0	100%	30
	2020	1396	43	0	100%	30
Land-based Wind	2030	1000	43	0	100%	30
	2040	950	42	0	100%	30

Note: EFF refers to efficiency, FIXOM refers to fixed operation and maintenance expenses and VAROM refers to variable operation and maintenance expenses. Data taken according to what was mentioned in the previous paragraph.

The solar and wind energy utilization factor was not taken from the NREL report, but instead, the Renewable Ninja tool was used (Pfenninger & Staffell, 2016; Staffell & Pfenninger, 2016), which using the 2019 MERRA-2 (global) database to calculate the average capacity factor annual for a specific location; then, the location of each of the

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oilfields was taken and the same assumptions made by Younis et al. in the use of this tool in the Colombian context were made (Younis et al., 2021): for solar energy, tilt and azimuth angles of 35° and 180 ° and system losses of 10% were assumed; For wind energy, an 80m hub height and the Vestas V9 2000 turbine model were assumed. The results were computed for each existing oilfield (CAM1-CAM7), while for the field that represents new discoveries (CAM8), since it did not have a defined location, it was decided to take the average of the existing fields.

Table C.4. Mean capacity factor for solar and wind energy.

Oilfield	Solar energy	Wind energy
CAM1	16,5%	38,7%
CAM2	15,7%	6,0%
CAM3	15,3%	4,3%
CAM4	14,7%	2,2%
CAM5	14,4%	1,0%
CAM6	15,6%	6,8%
CAM7	15,4%	5,3%
CAM8	15,4%	9,2%

Note: data computed using the above assumptions.

C.2 Hydrogen production

The model assumes that there is sufficient capacity to produce the hydrogen currently demanded in each of the refineries through SMR. Table C.5 details the technical-environmental parameters of this technology and proposes the option of using CCS and

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production of hydrogen by electrolysis to reduce emissions from this process. The emission factors of the technologies that use natural gas are determined by the combustion of natural gas and the rate of CO₂ capture, while electrolysis emissions depend on the emissions coming from the generation of electricity necessary for this process, which in this case will be of the national grid.

Table C.5. Hydrogen production options for both refineries (IEA, 2020b).

Technology	Parameter	2020	2030	2050	
Natural gas reforming	CAPEX	MUSD/PJ	28,86	28,86	28,86
	Eff	%	0,76	0,76	0,76
	Annual OPEX	MUSD/PJ	1,36	1,36	1,36
	Utilization factor	%		95%	
	Lifetime	years		25	
Natural gas reforming with carbon capture	CAPEX	MUSD/PJ	62,79	43,13	40,59
	Eff	%	69%	69%	69%
	Annual OPEX	MUSD/PJ	1,9	1,3	1,2
	CO ₂ capture rate	%	90%	90%	90%
	Utilization factor	%		95%	
Water electricity	CAPEX	MUSD/PJ	28,54	22,20	14,27
	EFF	%	64%	69%	74%
	Annual OPEX	MUSD/PJ	0,4	0,3	0,2
	Utilization factor	%	57%	57%	57%
	Stack lifetime	years	19	19	19

Note: The data for 2020 and 2050 were taken in reference to the "Today" and "Long term" periods of the IEA report.(IEA, 2020b)

C.3 Environmental policies

The demand scenarios taken exogenously from the PEN and the cost scenarios of decarbonization technologies for the TIMES model represent the inclusion of drivers that drive the decarbonization of the country in which the conceptual O&G company is located. However, the direct inclusion of other environmental policies that may represent a driver for decarbonization was considered, such as the carbon rate, and the demand and cost of hydrogen.

Regarding the carbon rate, the disruptive scenario contrary to assuming a constant value throughout the evaluated period of 2020-2050, assumes that there is an annual increase of 5% which is based on the discussions of carbon prices at the national level for other models (Calderón et al., 2016) and taking in consideration the international context (The World Bank, 2023a, 2023b, 2024). Furthermore, in the disruptive scenario, the scope of the carbon rate is expanded to all fossil fuels (in the base scenario, the coverage of the carbon rate was governed by current regulation, which has some exceptions such as natural gas and LPG. in certain sectors) and exports - which according to the results of the base scenario represent in some cases close to half of scope 3 emissions. The above allows the penalty for fuel use to be greater compared to current regulations.

Regarding hydrogen, the demand for this commodity was stipulated exogenously in accordance with the PEN to be consistent with the energy matrix in each of the sectors. Regarding the cost of hydrogen, the country's hydrogen roadmap was used as a reference, establishing the information that can be consulted in Table C.6. Furthermore, according to the roadmap, the following premise was established: gray hydrogen is not competitive due to its environmental implications from 2030, so that, by this date, the production of blue and green hydrogen must be prioritized.

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Table C.6. Market cost of grey, blue, and green hydrogen.

Source	COST~2020 (MUSD/PJ)	COST~2030 (MUSD/PJ)	COST~2050 (MUSD/PJ)
Grey	15.82	15.82	15.82
Blue	19.98	19.98	14.15
Green	23.31	23.31	14.15

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