

Article

Colombia's GHG Emissions Reduction Scenario: Complete Representation of the Energy and Non-Energy Sectors in LEAP

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Abstract: The signatory countries of the Paris Agreement must submit their updated Intended National Determined Contributions (INDCs) to the UNFCCC secretariat every five years. In Colombia, this activity was historically carried out with a wide set of diverse non-interconnected sector-specific models. Given the complexity of GHG emissions reporting and the evaluation of mitigation actions on a national scale, the need for a centralized platform was evident. Such approach would allow the integration and analysis of potential interactions among sectors, as well as to guarantee the homogeneity of assumptions and input parameters. In this paper, we describe the construction of an integrated bottom-up LEAP model tailored to the Colombian case, which covers all IPCC sectors. An integrated model facilitates capturing synergies and intersectoral interactions within the national GHG emissions system. Hence, policies addressing one sector and influencing others are identified and correctly assessed. Thus, 44 mitigation policies and mitigation actions were included in the model, in this way, identifying the sectors directly and being indirectly affected by them. The mitigation scenario developed in this paper reaches a reduction of 28% of GHG emissions compared with the reference scenario. The importance of including non-energy sectors is evident in the Colombian case, as GHG emission reductions are mainly driven by AFOLU. The first section describes the GHG emissions context in Colombia. Next, we describe the model structure, main input parameters, assumptions, considerations, and used LEAP functionalities. Results are presented from a GHG emissions accounting and energy demand perspective. The model allows for the correct estimate of the scope and potential of mitigation actions by considering indirect, unintended emissions reductions in all IPCC categories, as well as synergies with all mitigation actions included in the mitigation scenario. Moreover, the structure of the model is suitable for testing potential emission trajectories, facilitating its adoption by official entities and its application in climate policymaking.

Keywords: decarbonization; INDC; LEAP; energy modeling; long-term scenarios; GHG inventory



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1. Introduction

Committing to greenhouse gas emissions (GHG) reductions at the national and local level is necessary to minimize the climatic effects of global warming and increase the chances of not exceeding 2 °C in global temperature increase. To reach that goal, the signatory countries of the Paris Agreement are committed to periodically submitting their updated Intended Nationally Determined Contributions (INDC) [1]. Colombia has a GHG emissions profile dominated by the Agriculture, Forestry, and Other Land Use (AFOLU) sector, which in 2014 accounted for 54% of total emissions [2]. Deforestation, through the uncontrolled expansion of the agricultural and livestock frontier towards forested areas, is one of the leading GHG emission sources in the country. In 2014, the transport sector was responsible for 12% of the national GHG emissions, while energy industries accounted for 10% [2]. The Colombian Low-Carbon Development Strategy

(CLCDS) provided the framework for the discussion processes and modeling effort leading to the previous INDC formulation in 2015 [3]. In this process, several stakeholders such as the Ministry of Environment and Sustainable Development (MADS), the Ministry of Foreign Affairs (MFA), the National Planning Department (DNP), and academia had an important role.

For Colombia, the process of compiling and communicating GHG emissions accounting and scenarios was typically carried out by a wide set of diverse sector-specific models [3], which were then aggregated to build the INDC. Although in 2014 MADS and the UK government developed the Carbon Calculator 2050 [4], covering the most relevant sectors, the tool was not adopted by each ministry involved in defining future climate and GHG emissions scenarios. The Carbon Calculator had some limitations in capturing annual variations, possible synergies between sectors, and representing all sectors with a high level of detail, except for major cases (e.g., transport sector energy demand and fuel production). For instance, it did not have a dispatch module for the power sector based on a time-slice approach. Moreover, the representation of new technologies was time-consuming and cumbersome. To facilitate the integration and analysis of potential interactions among sectors and to guarantee the homogeneity of the general assumptions, the need for a centralized national system model was evident. Thus, the scenarios definition and development process is strengthened, as has been pointed out in the IRENA's long-term energy scenarios (LTES) [5].

This paper describes the process of developing—in the Long Emissions Analysis Platform software (LEAP)—a Colombia-tailored model (COL-NDC) to formulate the baseline emission trajectory for Colombia's 2020 INDC update and assess future energy needs, as part of a project jointly requested by the Colombian government and the World Bank. Previous LEAP models have been developed for Colombia focused on the energy sector [6–8]. Other studies have used LEAP to analyze the GHG emissions reductions in Colombia and other Latin American countries (i.e., Mexico, Chile, Panama) [9–13]. Conversely to these models, the COL-NDC model includes all energy and non-energy sectors, which provides a holistic approach to GHG emissions accounting and exploration of decarbonization scenarios. The model covers the emissions from all categories defined by the Intergovernmental Group of Experts on Change Climate (IPCC), which are Energy, Industrial Processes (IPPU), AFOLU, and Waste. A unique model is capable of handling interactions among mitigation measures adopted by different sectors (e.g., fugitive emissions reduction due to less extracting activities, which are a result of mitigation actions in-demand sectors). LEAP was chosen as it facilitates the construction of several scenarios using an accounting simulation approach, it can include non-energy sectors, it allows each sector to be modeled with a different approach according to the available data (e.g., top-down, bottom-up), and it does not require a technology-rich database. However, the tool also has some limitations, such as capturing the total system cost, endogenously defining the marginal price of products (e.g., steel price, space heating), and choosing the most cost-optimal scenario based on techno-economic parameters.

2. Methodology and Data

2.1. Data Gathering

Under the Colombian INDC update process, all the relevant Colombian ministries and several governmental organizations were involved in the design of the COL-NDC model structure, data pretreatment, definition of scenarios, and assumptions. Figure 1 shows the interaction and role of the stakeholders during the process, as well as their contributions.

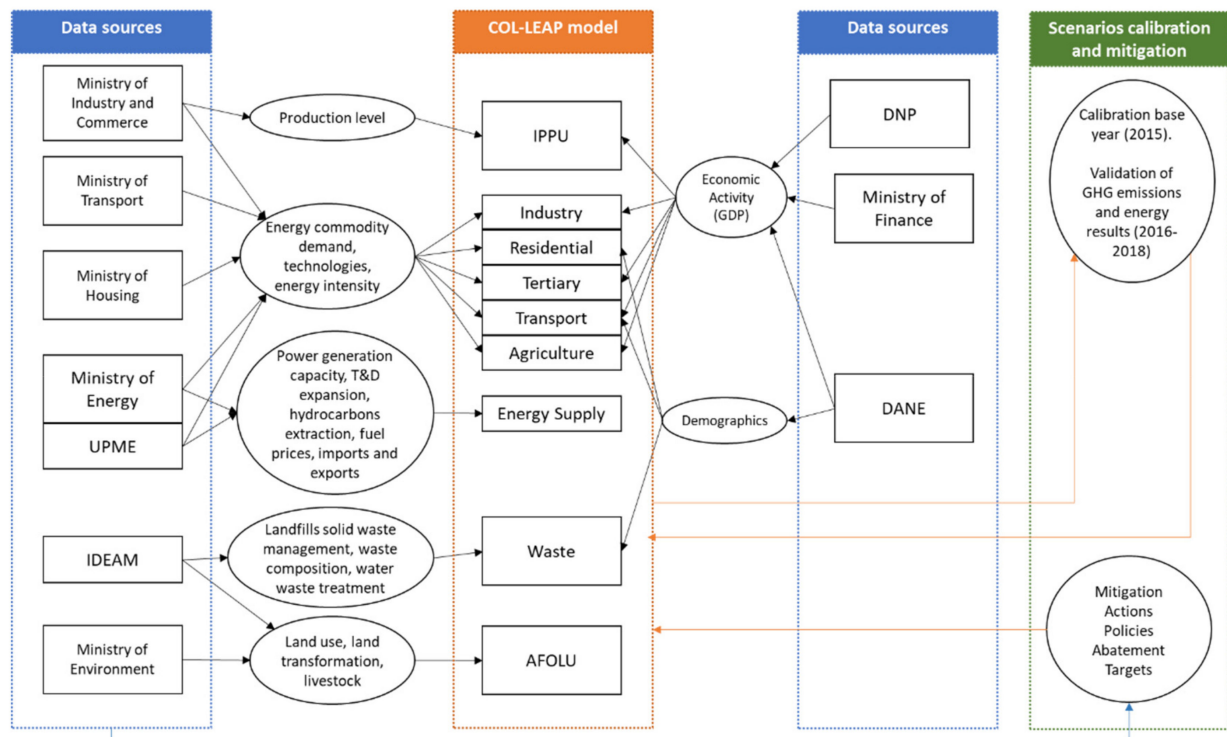


Figure 1. Stakeholders interactions and data exchange.

The COL-NDC model includes general macroeconomic and demographic parameters for the reference scenario as well as for the individual mitigation actions (see Table 1). The population is one of the main drivers of energy and GHG emissions. Therefore, the model includes the distribution of people living in rural and urban areas, as well as the size of households in both areas. National and sectoral GDP are used as main drivers for the industry, agriculture, for the energy demand of tertiary sectors; as well as for the stock of vehicles, industrial waste, and IPPU activity levels. Sectoral GDP projections are established by the DNP through the Colombian Computable General Equilibrium Model for Climate Change (MEG4C) [14].

Table 1. Macroeconomic and demographic assumptions.

Parameter	Units	2015	2020	2030	2050	Source
Population	Million	46.4	50.3	55.7	61.9	[15]
Urban areas	%	75.4%	76.0%	76.8%	76.0%	[15]
Rural areas	%	24.6%	24.0%	23.2%	24.0%	[15]
Urban household size	people	3.4	3.2	2.9	2.4	[15,16]
Rural household size	people	4.0	3.9	3.7	3.2	[15,16]
Annual GDP growth *	%	2.30%	3.40%	3.50%	-	[17,18]

* In 2020: −5.5% due to COVID-19. From 2021 to 2025: on average 5.2%.

2.2. LEAP Tool

The LEAP has been widely used for policy and scenario-based analysis, as well as for energy planning [19]. LEAP is an accounting-type simulation tool, which considers all energy requirements in the supply and transformation sector needed to meet future energy demands and report the associated GHG emissions. Additionally, GHG emissions also account for the non-energy sectors based on activity data and specific emissions factors (e.g., livestock, nitrogen content in fertilizers, biomass from deforestation). While LEAP was initially more energy-system oriented, it has undergone several updates to include additional features such as land use, indirect GHG effects (e.g., health, air quality), and emission cost of non-energy sectors. LEAP offers high flexibility to define the model topology and

the possibility to use bottom-up, top-down, and stock-turnover modeling approaches. Nevertheless, it is not possible to optimize the entire system based on a technology-rich approach as is the case of other modeling tools such as TIMES-MARKAL [20]. However, LEAP can quickly reflect the implementation of policies and mitigation actions, which eases the abatement potential and scope assessment of policies and mitigation actions by the comparison of several scenarios.

2.3. Structure of Colombian NDC LEAP Model

The COL-NDC model includes historical data from 2010 to 2014 to compare the trends of the projected period (2015–2050). Since the last official GHG inventory in Colombia dates from 2014 [2], this was selected as the base year for energy, activity data, and GHG emissions calibration. The period 2015–2018 is used to compare energy demand and emissions results from the model with official reports. The model uses several modeling approaches (e.g., top-down bottom-up, stock) based on the available data. For example, road transport is modeled considering the existing fleet (stock), vintage and exit curves, and annual sales. Conversely, the waste sector uses a top-down approach based on population and production of waste per capita. For IPPU, activity data is exogenously calculated and fed into the model, where GHG emissions are calculated considering default emissions factors. In the case of AFOLU, an already existing model for AFOLU, which is very detailed and flexible was used for the land use categories. Therefore, land and fertilizer-related emissions are endogenously calculated. On the other hand, emissions linked to livestock farming were completely modeled within LEAP using the number of animals and specific emissions factors by region and type of livestock. Figure 2 presents the general structure of the COL-NDC model and the main links among sectors. Global warming potential (GWP) with a horizon of 100 years is calculated taking into account the fifth assessment report (AR5) of the IPCC [21]. The emission factors (EF) for fuels are taken from a study carried out by the Ministry of Energy in Colombia to characterize the fuels used within the country [22,23]. When data is incomplete, default values from the IPCC guidelines are used. To facilitate the accountability of ministry-specific emissions and the compliance of their targets, GHG emissions are directly allocated in LEAP to the different ministries employing LEAP tags (Tags can be used to organize results that belong to more than one branch in LEAP).

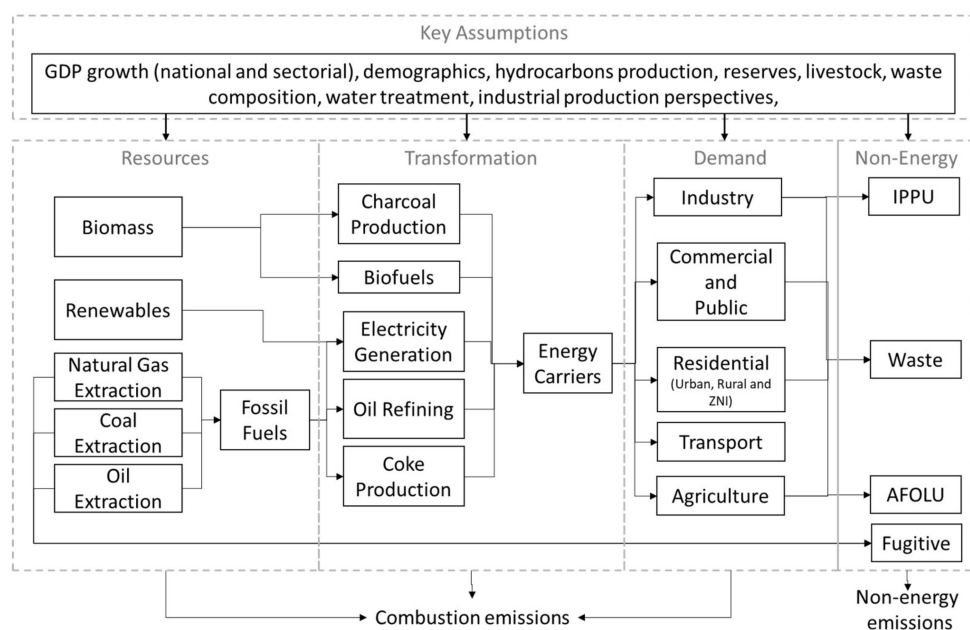


Figure 2. Colombia LEAP model structure.

2.3.1. Energy Demand Sectors Industry

The structure of the manufacturing industry subsectors is based on the Useful Energy Balance (UEB) (Useful Energy Balance makes reference to the useful energy used by end-use (e.g.: cooking, lighting), taking into account the efficiency of the technology and the final energy. This balance differs to the national energy balance (BECO)) [24], which disaggregates energy demand by seven end-uses, energy vectors, and the efficiency level, as is shown in Table 2. The energy demand of sectors not covered by the UEB follows the energy mix reported in the Colombian Energy Balance (BECO) [25]. The activity levels are linked to sectors. In this way, it is possible to calculate the useful energy intensity by end-use in terms of MJ/COP for each industrial sub-sector and specific end-use as the ratio of the useful energy demand of the specific end-use and the sectoral GDP. For the reference scenario, it is assumed that useful energy intensity will remain constant, and no major changes in fuel mix are expected.

Table 2. Industry structure by levels.

Sub-Sector	End Uses	Fuels	Equipment
1A2a—Iron and steel	1. Direct Heating	1. Bagasse	1. Existing efficiency
1A2b—Non-ferrous metals	2. Indirect Heating	2. Coal	2. Best efficiency available in Colombia
1A2c—Chemicals	3. Machine Drive	3. Natural gas	3. Best efficiency available worldwide
1A2d—Pulp, paper, and printing	4. Refrigeration	4. Firewood	
1A2e—Food, beverages, and tobacco	5. Cooling	5. Oil	
1A2f—Non-metallic minerals	6. Lighting	6. Waste	
1A2g—Transport equipment	7. Others	7. Charcoal	
1A2h—Machinery		8. Coke	
1A2j—Wood and wood products		9. Diesel	
1A2l—Textiles and leather		10. Fuel oil	
1A2m—Industry not specified		11. LPG	
1A2i—Mining and quarrying		12. Gasoline	
1A2k—Construction		13. Kerosene	

Transport

The transport sector is initially split into aviation, road transport, railways, shipping, and others (pipelines and off-road transportation) [26]. Road transport is further divided into additional categories (e.g., public, private, passenger, and freight transport). A top-down approach is selected for aviation, rail, and shipping due to the lack of information to further disaggregate their activity level. For these categories, national GDP drives the increase of energy demand. Conversely, road transport is modeled with a higher disaggregation level, considering the size of the vehicle fleet, fuel efficiency, and average annual activity. LEAP assesses annual GHG emissions based on fleet stock, vehicle activity (km/vehicle-year), and fuel consumption [27]. The total annual fleet in the base year was obtained from the national transport statistics (RUNT) [28]. RUNT data is used to derive vintage and exit curves for light passenger vehicles, motorcycles, light freight vehicles, buses, and trucks. The fleet converted to Compressed Natural Gas (CNG) is obtained from the statistics of the gas union [29] and RUNT. To obtain annual activity by category, the parameters included in two previous national studies are used [30,31]. For the freight sector, annual average activity data for trucks and tractors is taken from the database of the Ministry of Transport [28]. The equivalence between the BECO transport and IPCC categories is used to obtain the total vehicle-kilometers (VKTs) and their distribution by fuel. Average fuel consumption by category is defined according to the European Environmental Agency [32], the Fuel Economy database of the Department of Energy and the United States Environmental Agency [33], previous national studies [34–37] and confidential data provided by the Ministry of Transport (Table 3 summarizes the values used in the model).

Table 3. Fuel economy by fuel and type of vehicle for the base year [27,32–37].

Type	Natural Gas	Diesel	Gasoline
Units	MPG	MPG	MPG
Car	18.2	21.6	19.3
Bus	5.2	6.1	5.1
Medium Truck	5.8	8.8	7.9
Big Truck	3.9	5.9	5.3
Pick up	18.2	21.6	19.3
Micro Bus	11.9	13.9	12.5
Motorcycle	-	75.5	57.3
Taxi	18.2	21.6	19.3
Tractor	3.5	5.3	4.7

In the reference scenario, it is assumed that fuel economy annually improves by 1% between 2015 and 2030 for the new fleet, which is a conservative value considering that for emerging countries, there was an annual improvement of 1.2% between 2005 and 2017 [34]. For trucks and tractors, an annual improvement of 0.5% is considered in line with the improvements reported in similar markets globally [35]. It is assumed that the total vehicle fleet increases according to the GDP and population. Thus, the private transport fleet is modeled in terms of motorization rates using a Gompertz function [36] and two previous studies for Colombia [30,31]. This implies that the speed with which the fleet of light passenger vehicles has been growing, especially motorcycles, decelerates in the following decades. Freight transport fleet grows as a function of total GDP. Conversely, the projection of the public transport fleet responds to the coverage goals of this segment in urban transport, taking into account the participation of public transport according to the case study of the INDC 2015 [31].

Tertiary, Residential, and Agriculture

For the tertiary sector, the useful energy intensity for each end-use is defined from the UEB and sectoral GDP (see Table 4). The tertiary sector accounts for 5% of the total final demand in Colombia [25] and 60% of the national GDP [37]. Due to the variation in consumption patterns and expected GDP growth, this sector is broken down into the commercial and public sectors. It is assumed that useful energy intensity remains constant in the reference scenario. The energy mix is assumed not to undergo significant changes, following the trend of the last years [25].

Table 4. Useful energy intensity in MJ/COP [24,37].

End-Use	Commercial	Public
Water Heating	0.0143	0.0488
Cooking	0.0068	0.0024
Lighting	0.0034	0.0009
Machine Drive	0.0033	0.0019
Air Conditioning	0.0128	0.0046
Refrigerators	0.0010	0.0003
Others	0.0039	0.0054

The residential sector follows a similar approach to the one used for the tertiary sector. However, the demand, in this case, is attributed to households. Since consumption

patterns and fuel mix vary between households, this sector is divided into urban and rural households. Data on the size of rural and urban households is obtained from the National Department of Statistics (DANE) [38]. In the case of the residential sector, we define the useful energy intensity in terms of households in urban and rural areas (See Table 5). Due to the lack of information on the future development of useful energy intensity, it is assumed that these values will remain constant. Access to various energy services is an important determinant of energy consumption in the residential sector. According to the National Quality of Life Survey of 2015 (NQLS), 97.2% of urban households and 97.5% of rural households have kitchen facilities in their homes, while the proportion of households with a water heater is 24.5% and 4.1%, respectively [38]. In the case of TV, 92% of urban households have a television at home and it is projected that it will increase to 94% by 2030, reaching 97% coverage in 2050. In 2015, 87% of the urban homes have a refrigerator, 67% a washing machine, and 5% air conditioning (AC), while the respective figures for rural homes were 63.3%, 28.8%, and 1.2% [38]. With the increase of household income over time, access to these goods will increase. In 2030, it is expected that in urban areas 95% of households will have refrigerators, 85% will have washing machines and 10% will acquire AC. It is assumed that the adoption rate in rural areas will evolve similarly.

Table 5. Useful energy intensity in MJ/household [15,24].

End-Use	Urban	Rural
Cooking	2446	2661
Water heating	918	917
Lighting	57	40
TV	92	52
Air Conditioning	3599	3599
Refrigerators	403	403
Wash machine	119	119
Air Fan	49	64.5
Others	294	206

The energy demand of the agriculture sector in the BECO is used to determine the final energy intensity for each fuel used within the sector in terms of kJ/COP. Thermal energy intensity is established at 300 kJ/COP, electrical energy intensity at 43 kJ/COP, and machine drive intensity at 96 kJ/COP. We assume that final energy intensity will remain constant and sectoral GDP will be the main driver.

2.3.2. Supply and Transformation Sectors

The COL-NDC model is designed to represent the official projections of local production, imports, and exports of crude oil, oil derivatives, natural gas, and coal according to the official figures published by the Ministry of Mines and Energy [39–41].

The Power Sector

Power generation capacity is the one established in the Transmission Generation Expansion Plan 2016 (TGEP) [42]. Historical electricity generation and technical parameters of the plants are obtained from public reports by the power market operator (XM) and the Ministry of Mines and Energy [43]. Table 6 shows the efficiency by technology, calculated as the average ratio of the historical fuel consumption and electricity generation.

Table 6. The efficiency of power generation plants by technology [43].

	Diesel	Coal	Fuel Oil	Gas	Jet Gasoline	Fuel Mix
Efficiency	29%	32%	23%	44%	26%	33%

The power system is modeled reflecting the official expansion of the system up to 2030 as defined by the TGEP [42]. Table 7 shows the generation capacity in the reference scenario in 2030, complemented by the optimization feature available in LEAP [44].

Table 7. Reference power capacity mix [MW], [42].

	Hydro	Gas	Coal	Small Hydro	Biomass	Wind	Solar	Geothermal	Other	Total
2030	13,520	4470	1930	1260	0	362	90.5	0	88.3	21,720

The model also includes the energy for self-consumption, as well as the losses due to the transmission and distribution of energy in the national grid (SIN) and non-interconnected zones (ZIN). According to historical data, self-consumption is approximately 3% of the electricity generated and electricity losses are around 11% ($\pm 1\%$) [25]. National energy statistics show that the electricity generated by auto- and cogeneration is consumed mainly in the extraction of oil and natural gas (55%), followed by industry (40%) and injections into the SIN (5%) [25]. The average efficiency in the COL-NDC model for auto- and cogeneration plants is in line with reports of XM [45] and the National Energy Planning Unit (UPME) [46]. As Table 8 shows, in auto- and cogeneration natural gas, bagasse and diesel are the main fuels. The IPCC guidelines indicate that emissions must be accounted for in the sector where electricity from auto- and cogeneration is consumed. Consequently, a specific electricity commodity (Electricity_AUT_COG) is defined in the COL-NDC model to differentiate it from electricity from the national grid (Electricity_SIN). A specific EF is defined for the consumption of Electricity_AUT_COG, reflecting the fuel mix in the auto- and cogeneration module. Installed power generation capacity in ZNI was approximately 242 MW in 2019 [47,48], of which 96% were Diesel power plants and the remaining 4% renewable sources. To consider the trend growth of renewable sources in these areas, a conservative compound annual growth rate (CAGR) of 3% is assumed for the reference scenario.

Table 8. Fuel mix in auto- and cogeneration units (%) [25].

	2010	2011	2012	2013	2014	2015
Bagasse	14.9	13.4	13.9	14.2	16.3	16.2
Coal	8.9	9.1	9.6	7.9	9.2	9.2
Natural Gas	49	47.5	46.7	48.4	47.5	47.8
Hydro	0.6	0.7	0.6	0.6	0.6	0.5
Oil	11.9	15.6	15.6	13.1	11.9	11.8
Diesel	13.4	12.5	12.4	14.4	13.3	13.3
LPG	1.2	1.2	1.2	1.4	1.3	1.2

Fossil Fuel Extraction

The use of diesel and gasoline in coal mining is represented by intensity factors, that is, TJ of fuel used per TJ of coal produced (see Table 9). Exports are included as a restriction to be fulfilled by the model, according to the export levels defined by UPME [41]. Currently, more than 75% of the national oil production is exported. However, oil exports are expected to decrease, driven by higher local demand and current oil reserves levels. Annual oil production capacity is included in the model to ensure that it reflects official production projections according to the Liquid Fuel Supply Plan—2019 (LFSP) [39]. Without new additional reserves, national production is extinguished in the long term, and Colombia becomes a net importer in the reference scenario. The model includes the refining capacity

of 400 kbps [39], and no expansion is foreseen for the reference scenario. The extraction of natural gas in Colombia occurs mainly to supply domestic demand. Therefore, existing reserves (14EJ) were included in the base year [25,40], which will be depleted depending on the internal demand and the extraction capacity.

Table 9. Energy intensity in coal mining [25].

	Units	2010–2015
Coal production 2010-2015	[TJ]	14,701,512
Natural gas use in mining	[TJ]	8266
Diesel use in mining	[TJ]	88,303
Gasoline use in mining	[TJ]	584
Natural Gas Intensity	[TJ]/TJ _{Coal}	0.000562
Diesel Intensity	[TJ]/TJ _{Coal}	0.006006
Gasoline Intensity	[TJ]/TJ _{Coal}	0.000040

Other Fuels

Two independent modules are created for bioethanol and biodiesel production, which are limited to the current national capacity. These modules are created to enable Diesel-Biodiesel and Gasoline-Ethanol mixture modeling. The mix at the national level for the period 2010-2018 is obtained from historical data (3–7%) [25]. The model automatically calculates the EF of the mixed fuel discounting the biofuel energy share.

There are two classes of solid fuel production in Colombia: coke and charcoal. These processes are modeled considering the required auxiliary fuels and the EF related to the product based on IPCC values [26].

Fugitive

EF related to fugitive emissions are taken from IPCC default values (Tier 1) [26] and the average EF determined in Colombia for coal mining [49]. Fugitive emissions activity data is associated with the extraction of coal, oil, and natural gas, which are endogenous results in LEAP. Other parameters such as the amount of oil and gas transported and stored, the number of exploring wells and wells in service are obtained from historical values provided by the Ministry of Mines and Energy and included as average factors related to production level.

2.3.3. IPPU

IPPU in LEAP is based solely on the IPCC structure, for which information has been reported in the national GHG emissions inventory [2]. For mineral industries, data is obtained from UPME, the Colombian Mining Information System (SIMCO), the Annual Manufacturing Survey (EAM), and DANE. In the case of the chemical industry, production activity is directly obtained from companies within the sector, the national oil company (ECOPETROL), and the National Association of Businesses of Colombia (ANDI) (Confidential data provided during the World Bank PMR-Colombian NDC update project). Cement and ammonia production are currently operating at their maximum capacity and no expansion is foreseen. Therefore, the production will remain constant. The production of other sectors such as steel, ferroalloys, lubricants, glass, and lime are expected to grow in line with the sectoral GDP. For the case of Ozone Depleting Substances (ODS) substitutes, IDEAM and the Ozone Technical Unit (UTO) provided the emission time series of the respective substances for each subcategory.

2.3.4. AFOLU

In the case of livestock, the COL-NDC model considers 10 regions in Colombia, as the management of herds, feed and manure are different. For each region, specific CH₄ emission factors are used, both for enteric fermentation and manure management. Activity data and EF are provided by the Ministry of Agriculture and the Ministry of Environment.

Indirect N₂O emissions related to land use are calculated directly based on fertilization data, using the IPCC default factors for volatilization and leaching [26]. Projections based on historical values are used for the number of animals and the use of fertilizers as shown in Table 10. During a transition period of 20 years, land units are treated as converted land, and after those 20 years, the converted land units will be reported as land remaining as such. Total emissions from fuelwood extraction from all sectors are based on the energy demand for fuelwood resulting in the Energy sector in LEAP and translated into emissions in AFOLU.

Table 10. Expected growth and projections for AFOLU categories.

	Annual Growth	Source
Livestock	4.0% for Birds	FENAVI (National Federation of Poultry Farmers)
	1.5% for Pigs	PorkColombia (National Pig Farming Fund)
	According to historical annual growth	
Land burned	1% in biomass in cropland and grasslands 3% per year for forest land	IDEAM
Deforestation	2.9% for forested lands	IDEAM-(SMBYC)MEDS (Reference Level of Forest Emissions) [50]
	1.27% for croplands	
	1.02% for grasslands	
Forest plantations	According to the National Forest Development Plan	IDEAM

2.3.5. Waste

The GHG projection for the waste sector depends largely on population growth, while the industrial waste categories are driven by sector-specific economic growth. The main waste disposal systems currently used in Colombia are sanitary landfilling, open dumping, waste burning through incineration, open burning, and wastewater treatment. The sector follows a bottom-up approach where regional landfills have been individually modeled to reflect available disaggregated data into the model. The solid waste disposal category is based on the First Order Decay (FOD) methodology to estimate solid waste emissions coming from landfills [51]. As waste emissions are impacted by climatic parameters, the base structure of the waste module is divided into four climate zones relevant for the Colombian case (i.e., moist & wet tropical climate, wet temperate climate, dry tropical climate, and dry temperate climate) [51]. Waste incineration is linked to the activities of specific sectors or input assumptions within LEAP (e.g., coal extraction, population, sectoral GDP). Eight technologies are modeled for domestic wastewater treatment, differentiating between urban and rural areas. On the other hand, industrial wastewater is divided into seventeen industrial activities (e.g., sugar, pulp, and paper, food). Wastewater treatment is based on the IPCC Tier-1 methodology to estimate all the wastewater-related emissions.

3. Scenarios

3.1. Reference Scenario

The main drivers in the reference scenario are population and GDP, which are common to all scenarios (see Table 1). The relationship between these drivers and the growth of each sector is described in Section 2.3. In this scenario, mitigation policies established or implemented after 2015 are not included. Social phenomena such as migration to urban areas, the reduction of the size of households, and the increase of power purchase are reflected in the number of future urban and rural households, saturation rates of households' appliances and electronic devices, and motorization rates for private passenger vehicles (see Section 2.3.1). Moreover, the population has an impact on waste production and livestock activity, among others. The reference scenario accounts for the economic impact of COVID-19, which has a direct effect on energy consumption—mostly in the

industry, agriculture, and tertiary sectors—as well as in process-related emissions (IPPU) and industrial waste. Section 2 describes in more detail the assumptions and considerations for the reference scenario in each sector.

3.2. Mitigation Scenario

The mitigation scenario is the aggregation of individual mitigation actions. Since the potential of some measures is limited, these are grouped by affinity (e.g., energy efficiency measures, waste treatment measures) and pertinence (i.e., NAMA coffee and NAMA Panela energy efficiency). The mitigation scenario covers 44 measures which are listed in Table 11 (for more information see Appendix A, Tables A3–A6), proposed by each responsible ministry in the Colombian government as the result of previous and ongoing projects [52,53]. In LEAP, each mitigation action is individually modeled to assess its actual mitigation potential and limitations, as well as possible intersectoral synergies. When LEAP combines the individual mitigation actions into one aggregated scenario, such scenario inherits the parameters of the mitigation portfolio. Thus, in the case of mutual excluding mitigation actions (e.g., coal replacement with natural gas, and complete electrification of end-use), LEAP uses the expression of the last mitigation action in the inheritance order, therefore, the order must reflect the hierarchy, or priority, of the measures.

Table 11. Mitigation portfolio included in the mitigation scenario.

Sector	Mitigation Measure	Sector	Mitigation Measure
Energy	NAMA Refrigerators	Energy	Metro Bogotá
	Efficient new buildings		Intercity train Metropolitan Area
	Thermal districts		Compressors in pipelines
	Agriculture energy efficiency		Glycol use optimization
	Carbon tax		Recovery in storage tanks
	Demand management	IPPU	ODS substitutes
	Sustainable cement		Chemical industry
	Brick Development		Coffee and panela wastewater
	Industry Efficiency	Waste	Use of biogas in landfills
	Fuel replacement industry		Biogas management water treatment
	Thermal generator efficiency		Biogas burning in landfills
	Diversification Capacity Generation		Recycling of plastic paper and glass
	Mining energy efficiency		Biological mechanical treatment
	Energy Efficiency Refineries	AFOLU	Deforestation reduction
	NAMA TOD		AMTEC rice
	Aviation performance improvements		NAMA Coffee (land use)
	Scrapping and cargo fleet renewal program.		NAMA Panela (land use)
	Urban logistics improvements		Forest plantations
	NAMA TANDEM		Cocoa crops
	Freight transport—River/Road		Ecological restoration
Freight transport—Train/Road	Efficient wood stoves		
Electric mobility program	NAMA Livestock		

4. Results

4.1. Reference Scenario

National GHG emissions in the reference scenario are 346 MtCO₂-eq in 2030. AFOLU is responsible for 50% of the emissions, followed by Energy (36%). Table 12 shows the emissions of the reference scenario by IPCC category. Between 2015 and 2030, total GHG emissions grow with a Compound Annual Growth Rate (CAGR) of 2.7%, while the economy grows by approximately 3.5% each year. The growth rate of emissions changes after 2025, mainly driven by carbon sinks on land that remains as such and the reduction of deforestation, which compensates the increasing trend of the industry (CARG: 3.3%), the tertiary (CARG: 3.5%), and the transport sector (CARG: 3.6%). This tendency is due to the expected economic growth, the increase of the purchasing power, as well as the number of households, intensified by the reduction in the average number of people per household. Emissions associated with fuel combustion are mainly due to Diesel and coal, this reflects the increase of energy demand of the transport sector, heat demand in industry, and the use of coal power plants after 2025.

Table 12. GHG emissions results by IPCC category in reference scenario in MtCO₂eq.

IPCC Category	2015	2020	2025	2030
1—Energy	87	88	106	125
2—IPPU	9	11	15	18
3—AFOLU	118	170	186	175
4—Waste	19	22	25	28
Total	233	291	332	346

In terms of energy, total energy demand rises 724 TJ (+55%) from 2015 to 2046 PJ in 2030. National energy intensity decreases by 0.7% between 2015 and 2030, from 1.642 kJ/COP to 1.630 kJ/COP, being the tertiary sector the one with the highest change (-5%). Conversely, the energy per capita presents an upwards trend, increasing from 28.5 MJ/capita in 2015 to 36.7 MJ/capita in 2030. Table 13 shows the increase in demand by energy vector and their participation in 2015 and 2030. The most relevant energy vectors that increase the most are Diesel (+75%), gasoline (+72%), and electricity (+56%). Electricity demand in 2030 is 347 PJ, which is comparable with official results, 323 TJ (PEN-scenario-T1) [54] and 378 TJ (XM-Demand Forecast) [55].

Table 13. Energy demand by energy vector in 2015 and 2030 in the reference scenario.

	2010		2030	
	PJ	Share	PJ	Share
Coal	87	8%	99	5%
Natural Gas	170	15%	296	15%
Wood	154	14%	146	8%
Gasoline	148	13%	340	18%
Diesel	223	20%	468	24%
Coke	16	1%	1	0%
LPG	29	3%	45	2%
Kerosene	36	3%	82	4%
Electricity	190	17%	335	17%
Other fossil	22	2%	12	1%
Other	53	5%	93	5%
Total	1126		1916	

4.2. Mitigation Scenario

In 2030, total GHG emissions in the mitigation scenario decrease by 96 MtCO₂eq to 250 MtCO₂eq, equivalent to a reduction of 28%. There is a heterogeneous distribution of the

GHG emissions reduction among IPCC sectors, as can be seen in Figure 3. In the mitigation scenario, 79% of the reductions are attributed to AFOLU, mainly by the reduction of deforestation. The remaining reduction is distributed in Energy (18%), IPPU (2%), and Waste (1%). Figure 4 presents the energy demand and GHG emissions in 2030 by sector. In most cases, there is a reduction of energy demand due to energy efficiency measures, technology replacement and the switch to more efficient fuels (e.g., from coal and firewood to natural gas or electricity). However, the increase of natural gas demand leads to an increase of emissions upstream, namely production, pipelines energy consumption, and fugitive emissions. Moreover, GHG emissions decrease in almost all energy demand sectors by an average of 12% in 2030. The transport sector can reduce 6 MtCO_{2eq} by a combination of modal changes, electric vehicles, and improvements in the logistics of freight transport.

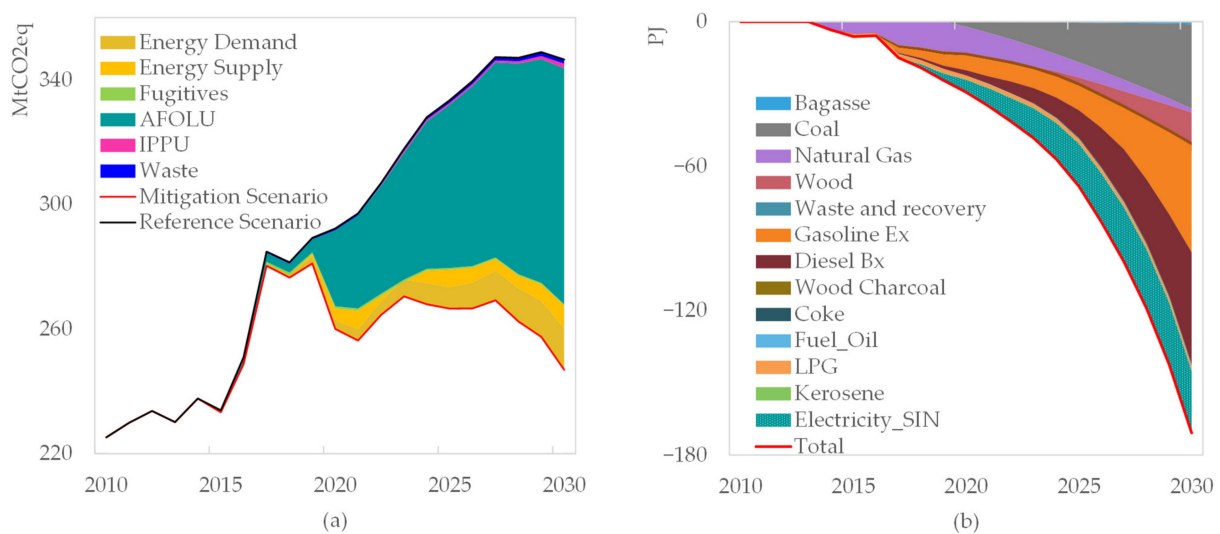


Figure 3. (a) GHG emission reductions by IPCC category and (b) energy demand changes by energy vector in the mitigation scenario compared with the reference scenario.

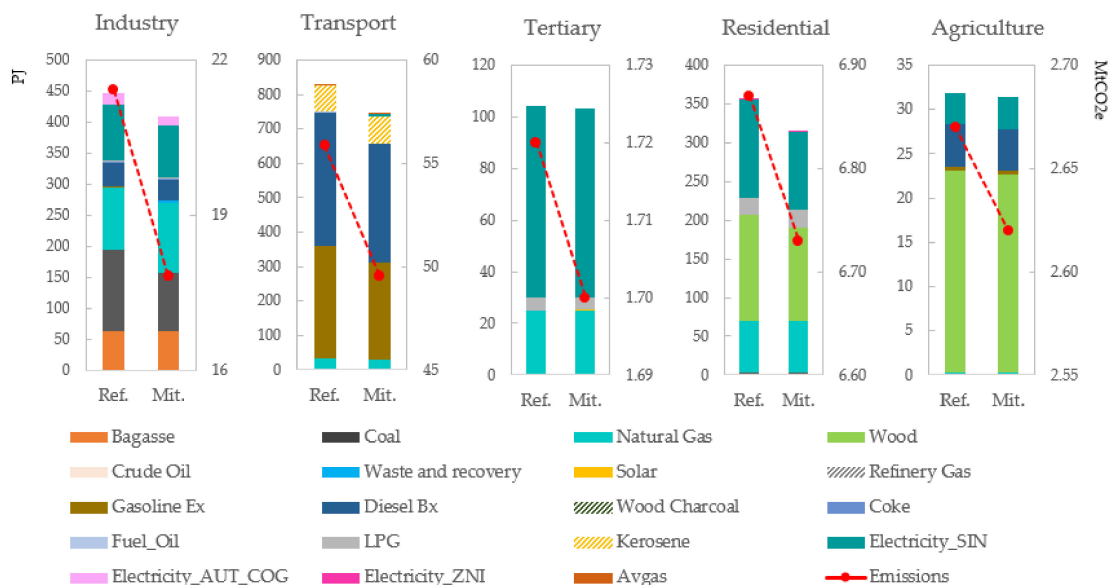


Figure 4. Energy demand and GHG emissions by demand sector in the reference and mitigation scenarios. Right axis in PJ and left axis in MtCO_{2eq}.

The potential of individual measures might differ from the actual mitigation in the mitigation scenario due to the implementation of other mitigation alternatives. For ex-

ample, by reducing the emission factor of the power sector due to the penetration of non-conventional renewable energies (indirect measure), the potential for reducing energy efficiency measures decreases (direct measure). A second case of these synergies occurs when the measures directly affect the same sector or category. For example, in the transport sector, a transport modal change measure such as the construction of a subway in the main cities (initial measure) will result in a reference scenario different than the initial one for the following measures. Hence, an additional measure such as promoting the use of bicycles will have a lower number of possible users than in the case of not having the subway as a means of transport. Table 14 shows the individually estimated emission reduction potential and the actual potential in the mitigation scenario by IPCC category.

Table 14. Mitigation potential of mitigation actions by IPCC category, comparing individual (standalone) and combined potential in mitigation action in MtCO_{2eq}.

	Individual Potential	Mitigation Scenario	Variation
Energy	21.1	17.2	−18.1%
IPPU	1.4	1.6	+12.1%
AFOLU	75.8	75.7	−0.2%
Waste	1.3	1.2	−9.5%
Total	99.6	95.7	−3.9%

5. Conclusions

LEAP demonstrates to be an adequate tool to keep complete historical GHG emissions inventories and build future scenarios. It also allows to correctly assess the actual mitigation potential of some mitigation actions when interacting within a mitigation portfolio in a combined scenario. Although in 2020 total emissions start decreasing, this is mainly due to improvements in land management (deforestation and conservation). Therefore, there is still room for improvement in energy demand sectors, which keep an upward trend. By 2028, modal changes in passenger transport have a relevant effect on Diesel and gasoline demand. This highlights the importance of mass public transportation systems in the main cities from a climate perspective. The industry has the chance to replace the use of coal for thermal uses with natural gas, which might be a solution for the transition towards a low carbon scenario in the long term. Since the use of firewood in the residential sector slightly changes, the promotion of cleaner ways of cooking could have a considerable impact on GHG emissions and population health. Non-energy sectors should be carefully modeled to properly capture real intersectoral synergies since LEAP does not include those interactions by default. However, this approach also presents some limitations. Non-energy sectors must be modeled from a user-defined approach, which increases the computation burden of the model and the risk of mistakes. Moreover, a detailed representation of intersectoral connection in the model according to the user considerations might prevent replicability and lead to neglecting possible interactions. Lastly, scenarios and results are highly susceptible to main assumptions and user expectations as LEAP does not include optimization of demand and non-energy modules-based technology-rich alternatives, which might lead to the definition of less likely scenarios.

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Appendix A Complementary Tables

Table A1. Refineries energy demand [25].

		2010	2011	2012	2013	2014	2015	Average
Refined Oil	[PJ]	666	680	678	631	548	542	624
Energy consumption	[PJ]	51	56	56	55	47	53	53
Energy Intensity	[PJ]/[PJ]	0.077	0.083	0.082	0.087	0.085	0.098	0.085
Share								
Diesel	[%]	0.02	0.04	0.06	0.01	0.02	0.02	0.03
Fuel Oil	[%]	5.55	5.65	0.56	0.45	0.03	0.05	2.08
Refinery Gas	[%]	29.87	28.57	28.52	22.11	13.72	12.75	22.83
LPG	[%]	2.93	2.44	3.80	5.45	7.41	16.20	6.31
Natural Gas	[%]	61.61	63.29	67.05	71.98	78.82	70.97	68.74
Gasoline	[%]	0.00	0.00	0.00	0.00	0.00	0.01	0.00
Kerosene	[%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Source: Ministry of Mines and Energy.

Table A2. Fugitive emission factors for mining in m3/ton.

Region	Mining		Post-Mining	
	CO ₂	CH ₄	CO ₂	CH ₄
Cundinamarca	0.077	13.03	0.018	3.909
Boyacá	0.077	7.17	0.018	2.151
N Santander	0.077	7.17	0.018	2.151
Antioquia	0.077	2.93	0.018	0.879
V Cauca	0.077	2.93	0.018	0.879
Cauca	0.077	2.93	0.018	0.879
Casanare	0.077	1.95	0.018	0.585
Average Underground	0.077	8.926	0.018	2.678
Cesar	-	0.89	-	0.267
La Guajira	-	0.89	-	0.267
Santander	-	0.4	-	0.12
Córdoba	-	0.59	-	0.177
Average surface	-	0.888	-	0.266

Source: [22,23,26,56].

Table A3. Mitigation actions of the energy sector included in the mitigation scenario.

Scope	Mitigation Measure	Explanation	Target 2030	Assumptions	Implementation in LEAP
Residential sector	NAMA Refrigerators	Change the coolant used in national production and imports of refrigerators, which would reduce the electricity demand of the refrigerators stock.	More efficient refrigerators: 60% of national stock	Replacement will be the result of the natural replacement of obsolete stock.	Change of the share of technology in the residential sector

Table A3. Cont.

Scope	Mitigation Measure	Explanation	Target 2030	Assumptions	Implementation in LEAP
Residential and tertiary	Efficient new buildings	Improve the efficiency of new buildings by better materials use and novel design techniques.	20% reduction of energy intensity [MJ/m ²] foal all new buildings	The area will grow by 23 million m ³ . Savings are only in terms of electricity demand.	Reduction of energy intensity in proportion to the expected area of new buildings and efficiency targets and penetration of more efficient technologies.
Tertiary sector	Thermal districts	Avoid the installation of air conditioning systems by the thermal district in public and commercial buildings.	90 Million refrigeration tonnes	Without thermal districts, conventional AC would be used.	Switch demand from the AC category to thermal districts module by reducing energy intensity [MJ/COP]
Agriculture and fishing	Agriculture efficiency (panela and coffee NAMA)	Change of diesel engines for electric engines, and increase the use of biomass for thermal processes in a more efficient manner.	Replace 50% of fossil fuels with biomass in coffee and panaela crops, and improve the efficiency of the thermal process by 2%	The measure could be equally implemented in all farms/production sites.	Modification of energy intensity factor in proportion to the share of coffee and panaela energy demand in the agriculture-fishing sector.
Transport, industry, and supply	Carbon tax	Impose a tax on fossil fuels in certain sectors such as transport, refineries, and industry. Demand will respond to price increase according to specific elasticities defined for each sector.	US\$7/tCO ₂	Lineal and general demand elasticity to fuel price increase	Modification of energy intensity in relation to sector-specific elasticity and CO ₂ content of energy vector.
All demand sectors	Demand management	Promote demand response through the introduction of aggregators and incentives.	Reduce by 20% the difference between the peak and valley of the annual electricity demand load curve.	Demand management will be possible with aggregators, smart meters, and incentives to the industry.	Change of the system load curve
Industry	Sustainable cement	Increase the use of biomass and solid waste in the kiln.	15% of kiln energy needs cover with biomass and waste	It is possible to replace coal with biomass and waste without modifying the kiln	Change of fuel mix
	Brick Development	Replacement of coal and liquid fossil fuels with natural gas and biomass.	Fuel mix: 60% natural gas and 40% charcoal and firewood in thermal processes	Current technology can operate with future fuel mix	Change of fuel mix
	Industry Efficiency	Promote energy efficiency programs aiming to improve production practices, and to a lesser extend equipment.	Technologies with better efficiency will reach 30% indirect heat and other end-uses.	It is possible to replace 30% of the technologies (e.g., engines, boilers, compressors). Replacement also reflects changes in production behavior.	Share of the best technology in Colombia/international

Table A3. Cont.

	Fuel replacement industry	Replacement of coal and liquid fossil fuels with natural gas (when suitable)	Replace 20% of liquid fossil fuels with natural gas	There is a different potential by sector	Change of fuel mix
Electricity supply	Thermal generator efficiency	Preventive and corrective maintenance to augment the efficiency of coal and natural gas power plants.	Increase by 2% the energy efficiency of coal and natural gas power plants	The measure will apply to all coal and natural gas power plants. Maintenance will correct efficiency degradation due to normal operation.	Increase the efficiency of the technology (coal or natural gas) to the desired level.
	Diversification Capacity Generation	Increase the penetration of wind and solar in the generation mix. Additionally, include biogas and geothermal in the generation mix.	Capacity defined in PEN 2015	The power capacity proposed in the Colombian energy plan will match the future electricity demand	Change the exogenous capacity according to the Colombian energy plan (PEN)
Coal extraction	Mining energy efficiency	Improve the efficiency of the mining activities without changes in technologies nor fuel mix.	Reduce energy intensity of electricity and diesel by 1%.	Changes in production techniques/processes reach energy reductions without technology changes	Change of auxiliary fuel intensity
Oil refining	Energy Efficiency Refineries	Improve the efficiency of refining activities without changes in technologies nor fuel mix.	Reduce by 16% energy intensity of refineries (feedstock not included)	Changes in production techniques/processes reach energy reductions without technology changes	Change of auxiliary fuel intensity
Transport	NAMA_TOD	Nationally Appropriate Mitigation Action—Transport Oriented Development (TOD).	The goal is to implement four TOD projects in four cities. The goal is to reduce motorized activity in 2030 with respect to BAU: Passenger light: 0.7%; Taxis: 0.6%; Buses: 0.4%; Medium trucks: 0.01%.	Despite this type of intervention take time to consolidate, it was assumed they will be in place since 2021 and there will be results in emissions since then.	Modal share changes. We create a technology to represent non-motorized modes, with no energy consumption.
	Aviation performance improvements	Performance-Based Navigation (PBN) in domestic aviation.	The mitigation action proposes to cover 60% of the national airports, to improve the fuel efficiency of the commercial flights.	It was assumed some airports won't be able to implement PBN in the next years, so the action affects only a proportion of the domestic operations.	Reduction in fuel intensity factors.

Table A3. Cont.

Scrapping and cargo fleet renewal program.	It consists of disintegrating and renovating the oldest vehicles in the cargo fleet. It affects trucks with a gross vehicle weight greater than 10.5 tons and more than 20 years old.	The program seeks to renovate 57,000 trucks between 2015 and 2030.	Older trucks tend to be used much less than new trucks, and that might affect the potential to reduce CO ₂ eq. It was assumed that the program is accompanied by the optimization of freight operations, so in the end, the net effect is positive.	It is represented using the scrapping and fraction of scrapped replaced functions.
Urban logistics improvements	Urban logistics improvements in the main cities in the country.	These mitigation actions seek to improve the operation of urban logistics in the main cities in the country.	It was assumed that the potential to improve current practices is significant. It is assumed that a national program will be able to cover almost 100% of the operations since the beginning of the action in 2017. This action depends on many external factors, and this is not captured by the assumptions in the model.	Modal share changes. We create a technology to represent avoided activity per year.
NAMA_TANDEM	Nationally Appropriate Mitigation Action—Active transport and travel demand management (TAnDem).	It seeks to promote the use of non-motorized modes in urban passenger transport. The goal is to reduce motorized activity in 2030 with respect to BAU: Passenger light: 0.6%; Taxis: 1.6%; Motorcycles: 0.2%.	It is assumed that the action is generating benefits in GHG emissions since its beginning in 2019. The potential was modeled considering the effects of similar projects in Colombia and Latin America.	Modal share changes. We create a technology to represent non-motorized modes, with no energy consumption.
Multimodal freight transport—River/Road	Increase the participation of waterborne transport in the freight segment.	By modal substitution, the goal is to reduce between 30,000–132,000 t CO ₂ eq per year in the period 2016–2030.	It is assumed that the main benefits will come from the proportion of freight transport by the river, but there is also an opportunity to improve the road complementary segment.	Modal share changes in road transport. Increase in fuel intensity factors for navigation.
Multimodal freight transport—Train/Road	Increase the participation of rail transport in the freight segment.	By modal substitution, the goal is to reduce between 9000–112,000 t CO ₂ eq per year in the period 2021–2030.	It is assumed that the main benefits will come from the proportion of freight transport by train, but there is also an opportunity to improve the road complementary segment.	Modal share changes in road transport. Increase in fuel intensity factors for trains.

Table A3. Cont.

Electric mobility program	Increase the participation of electric vehicles.	In terms of activity (VKTs) in 2030 there is this participation of electricity: Passenger light: 22%; Taxis: 5%; Buses: 10%; Medium trucks: 8%.	It is assumed the incentives and other complementary programs will be implemented on time to reach the goal in the electric fleet by 2030.	Sales share changes in road transport.
Metro Bogotá	The first line of the Bogotá Metro.	By modal substitution, the goal is to reduce 132,000 t CO ₂ eq per year in the period 2028–2030.	It is assumed that the substitution effects will be gradual and so will be the effects in emissions reduced.	Sales share changes in road transport.Modal share changes.
Intercity train Metropolitan Area of Bogota	Regional tram to serve the Metropolitan Area of Bogotá.	By modal substitution, the goal is to reduce 32,000 t CO ₂ eq per year in the period 2024–2030.	It is assumed that the substitution effects will be gradual and so will be the effects in emissions reduced.	Sales share changes in road transport.Modal share changes.
Compressors in natural gas activities	Improve the sealing of compressors in the extraction and transportation of natural gas.	20% less emission in venting	Works on compressors will be lineal from 2018 to reach the target in 2030.	Reduction of emission factor
Fugitives	Glycol use optimization	Reduction of emissions by 2%	The reduction of the emission factor reflects the potential assed in some wells in Colombia. This can be extrapolated to the total national production.	Reduction of emission factor
	Recovery in storage tanks	13% less emissions in distribution	All storage facilities might reach the same level of reduction as the pilot projects in some facilities in Colombia have done *.	Reduction of emission factor

Table A4. Mitigation actions of IPPU included in the mitigation scenario.

Scope	Measure	Explanation	Target 2030	Assumptions	Implementation in LEAP
Substances	ODS substitutes	Reduce the use and management of ODS substances	Reduce the use of the most polluting HFCs by 15%	The replacement of substance with other HFCs is possible without affecting the performance of cooling technologies and there will be market acceptance.	Change in production activity
Process emissions	Chemical industry	Reduce process emissions in the industry by improvements in reactions	Reduce 10% process emission in nitric acid production	An emission factor lower than the standard IPCC is possible by improvements in production.	Reduction of emission factor

Table A5. Mitigation actions of AFOLU included in the mitigation scenario.

Scope	Measure	Explanation	Target 2030	Assumptions	Implementation in LEAP
Wastewater	Nama coffee and panela wastewater treatment	Wastewater treatment of coffee and panela farms	5% of water treated with septic tank and burning of 4ktCH ₄ .	All farms are similar and have access to wastewater treatment facilities close to production.	Change in the share of technologies in residential-rural and industry-coffee/sugar wastewater management
	Use of biogas in landfills	Use of landfill gas for the production of electricity	3% of CH ₄ emissions in major landfills	The production of electricity in landfills covers local electricity demand. Surplus of electricity is neglected.	CH ₄ recovery variable in function of emission in reference scenario
	Biogas management water treatment	Recovery of CH ₄ in wastewater treatment plants to destroy CH ₄ molecules and emit CO ₂ .	35% wastewater treated with plants with CH ₄ recovery	Recovered CH ₄ is used to partially cover sites own energy requirements (electricity and heat)	Change in the share of technologies in residential-urban wastewater management
Solid Waste	Biogas burning in landfills	Recovery of CH ₄ in landfills to destroy CH ₄ molecules and emit CO ₂ .	1.5% of CH ₄ emissions	Combustion is efficient and most CH ₄ molecules are destroyed	CH ₄ use variable in function of emission in reference scenario.
	Recycling of plastic paper and glass	Increase the recycling rate of plastic, paper and glass at national level.	15% in major landfills	Recycling is possible in landfills linked to the five biggest cities. Waste sorting is done outside the landfill facilities.	Change in the amount of solid waste (plastic, glass, and paper disposed) in landfills used in the calculation of emissions.
	Biological mechanical treatment systems	Composting of organic component of municipal solid waste to prevent CH ₄ emissions.	5% of biological part of waste in major landfills	Organic waste is extracted at the entrance of the landfill	Reduction of the amount of municipal solid waste reaching landfills, and a proportional increase in the solid waste treated by mechanical biological treatment plants.

Table A6. Mitigation actions of Waste sector included in the mitigation scenario.

Scope	Measure	Explanation	Target 2030	Assumptions	Implementation in LEAP
	Deforestation reduction	Deforestation rates are reduced following the ambitions included in the NREF	Reduction of 40kha/yr	Reduction of deforestation linked to illegal activities, intensive agriculture and intensive mining, among others is possible by policies, regulation and surveillance of protected areas.	Results are fed from AFOLU model (exogenous) into subcategories 3B1
	AMTEC rice	Implementation of AMTEC mode for rice production: Volumetric water consumption management; reduction in the use of fertilizers in the productive system; and management of harvest residues.	80% of crops	De adoption of the AMTEC method by rice producer will not present opposition	Results are fed from AFOLU model (exogenous) into subcategories 3C4 y 3C5
Land use	NAMA Coffee (land use)	Implement strategies for the mitigation of GHG generated in the production, harvest and post-harvest stages of Colombian coffee at the farm level.	1.2 kHa/yr. of crops with shade	The benefits of crops with shade are the same in all regions and conditions	Reduction of fertilizer used by coffee crops.
	NAMA Panela (land use)	Encourage the efficient use of synthetic fertilizers and promote the reduction of burns	1500 sugar mills with 800 ha of restoration	Data from the "Andina" region are extrapolated to the national level (14.8 tCO ₂ /ha/year.)	Results are fed from AFOLU model (exogenous) into subcategories 3B2bi
	Forest plantations	Increased establishment of forest plantations in non-forest areas prior to planting	15 kha/yr	Plantation harvesting is within a cycle equal or less than one year.	Results are fed from AFOLU model (exogenous) into subcategories 3B2a.
	Cocoa crops	Increase in areas dedicated to the cultivation of cocoa under agroforestry systems (SAF), and land rehabilitation.	80k Ha	Given that for the productive sector only 7.6% of the productive units use chemical fertilizers and 6.5% apply organic fertilizers, the use of fertilizers will not be taken into account in the quantification of emission reductions.	Results are fed from AFOLU model (exogenous) into subcategories 3B2a.
	Ecological restoration	Reforestation of already deforested lands	1 million Ha	Land will be restored and protected 20 years. Then, land will pass to the category of land that remains as it is.	Results are fed from AFOLU model (exogenous) into subcategories 3B2a.

Table A6. Cont.

Scope	Measure	Explanation	Target 2030	Assumptions	Implementation in LEAP
Biomass use	Efficient wood stoves	Provide more efficient firewood stoves to households that currently use firewood for cooking	700,000 new stoves	People will continue using firewood for cooking. New stoves will improve efficiency and reduce wood consumption per capita in rural areas.	Increase penetration of effect stoves in demand sector (residential—rural).
Livestock	NAMA Livestock	Reduce GHG emissions generated in livestock production and increase carbon removals from ago-ecosystems dedicated to livestock by intensifying the production of livestock systems and increasing efficiency (less land for animal farming).	38% of livestock farms. Emission factor reduction of 0.55%. And 68kHa of livestock farming to be restored.	1% less fertilizer for 27% of cattle. Almost all land restoration is attributed to 1 of the 10 defined regions,	Reduction of CH ₄ emissions by enteric fermentation. Reduction of nitrogen fertilizers. And carbon sequestration in soils and biomass from a series of measures (From AFOLU land model)

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