Informing Sustainable Energy Policy in Developing Countries: An Assessment of Decarbonization Pathways in Colombia Using Open Energy System Optimization Modelling

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Abstract

Colombia is committed to reducing its greenhouse gas (GHG) emissions by 51% by 2030 as part of the Paris Agreement, with a further goal of achieving carbon neutrality by 2050. The energy sector accounts for one-third of net GHG emissions in the country; thus, its decarbonization is crucial to accomplish these targets. In this study, we assess plausible decarbonization pathways using an open-source national energy system optimization model (OSeMOSYS). We build three scenarios over 2021-2050 and contrast them in terms of emissions, energy consumption, technology deployment, costs, and benefits. The results show that a decarbonized energy system can reduce carbon intensity by 93%, energy intensity by 44%, fossil fuel imports by 90%, and provide socioeconomic benefits equivalent to 21% of the Colombia's 2021 GDP. We use these results to recommend milestones and policy actions that can help inform policymakers about cost-effective strategies to achieve a sustainable, efficient, and more resilient energy system by mid-century. Our transparent and systematic methodology provides a tool for long-term energy planning in Colombia which can also be replicated in other developing countries for assessing decarbonization pathways.

Keywords: energy system, optimization modelling, decarbonization, OSeMOSYS, scenario analysis, energy policy.

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Nomenclature

Acronyms

GHG	Greenhouse gases
OSeMOSYS	Open-source energy modelling system
ESOM	Energy system optimization model
SDG	Sustainable development goal
NAMA	Nationally Appropriate Mitigation Action
LPG	Liquified petroleum gas
LNG	Liquified natural gas
CCS	Carbon capture and storage
INS	Interconnected National System
SMR	Steam Methane Reforming
BEV	Battery electric vehicle
PHEV	Plug-in hybrid electric vehicle
FCEV	Fuel cell electric vehicle
UPME	Mining and Energy Planning Unit
GDP	Gross Domestic Product
NIZ	Non-Interconnected Zone
O&M	Operation and maintenance
IPSE	Promotion and Planning Institute for Energy Solutions
AFOLU	Agriculture, Forestry, and Other Land Uses
PP	Power Plant
ICE	Internal combustion engine
BECCS	Bioenergy with carbon capture and storage
SMR*	Small modular reactor
LTS	Long-term strategy
NEP	National energy plan
UVT	Tributary value unit
CLEWs	Climate, land, energy, and water systems

1. Introduction

The energy sector in Colombia accounts for one-third of the country's net emissions [1], with transport, power generation and industry being the primary contributors to GHG emissions in the energy sector. In this context, Colombia is one of the 11 most vulnerable countries to global warming and climate change [2], and is committed to achieving carbon neutrality. As a signatory to the Paris Agreement, Colombia aims to limit global warming to below 2°C compared to pre-industrial levels and pursue efforts to keep it below 1.5 °C [3]. In its most recent 2020 National Determined Contributions (NDC), Colombia set a target to reduce GHG emissions by 51% by 2030 and attain carbon neutrality by 2050 [4]. The NDC also outlines measures to achieve mid-term targets (2030) and their contribution to different Sustainable Development Goals (SDGs). Additionally, the Colombian Ministry of Environment and Sustainable Development has developed the Long-Term Strategy (LTS) called E2050, which provides guidelines for mitigation and adaptation to achieve a climate-resilient country and a carbon-neutral economy by 2050.

The development of future updates of the NDC and the ongoing formulation of sectoral strategies for the LTS will require robust energy planning tools [5,6]. Energy system optimization models (ESOMs) are recognized as effective instruments to support governments and decision-makers in the development of long-term decarbonization policies [6–9]. When ESOMs are coupled with open data and open-source methods following the U4RIA principles [10], outcome analysis and policy insights are broadly acknowledged due to enhanced transparency, public trust, and scientific reproducibility [5,11–13]. Integrated energy planning that combines open models, stakeholder engagement, and local capabilities development has proven to deliver successful performance and mobilization of significant financial resources [14]. The Data-to-Deal approach created a workflow in Costa Rica that is worth replicating in other developing countries. The process began with the launch of the data-driven national decarbonization plan in 2019 and has successfully secured approximately 2.4 billion dollars of international concessional finance by the end of 2022 [14]..

Previous studies have explored national energy system modelling in Colombia through different methodologies and scopes, as described in section 1.2. Nevertheless, to the best of our knowledge, no prior work provides an integrated energy analysis of the decarbonization pathways in Colombia using open data and open-source ESOM. Hence, this research aims to fill this gap and deliver an open methodology to conduct energy planning in Colombia, enabling further collaboration between stakeholders and researchers. We implemented the OSeMOSYS framework to build three scenarios over the period 2021-2050, covering the business-as-usual (BAU) state, a decarbonization pathway with all technologies available, and an alternative decarbonization pathway without carbon capture and storage (CCS). Our findings demonstrate the technical feasibility and socioeconomic benefits of pursuing decarbonization goals in Colombia as opposed to a BAU scenario by 2050.

This paper is structured as follows: the remainder of section 1 summarizes Colombia's current energy system, and reviews relevant literature. Section 2 presents the modelling methodology, input data, and scenario analysis. Section 3 presents the results, while section 4 discusses the study's main findings, policy insights, and limitations. Finally, section 5 presents the concluding remarks.

1.1. Context

Colombia is a developing country located in South America, characterized by the extraction of primary materials such as coal, oil, and natural gas and relatively low levels of industrialization [15]. Colombia has increased energy consumption from 728 PJ to 1336 PJ between 1975 and 2019, driven by population and economic growth [16]. In 2021, the consumption from primary energy resources reached 1435 PJ (Figure 1), with fossil fuels – including coal and natural gas for electricity generation – representing around 70%. The share of fossil fuels in the total energy production represented 75% in 2021.

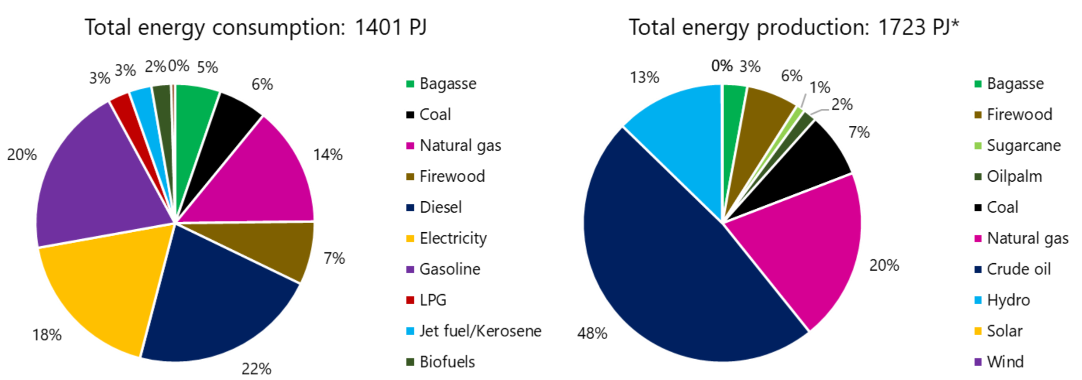

Figure 1. Colombian end-use energy and energy production in 2021 [17]
*Crude oil and coal exports are not included

Colombia's power sector has an installed capacity of 17.79 GW within the Interconnected National System – SIN [18], with the largest share of capacity being hydroelectric sources, including both dams and run-of-river plants (Figure 2). Thermal capacity, which includes natural gas, coal, and oil derivatives, makes up around 30% of the installed capacity, while solar, wind, and biomass sources have a marginal share. Furthermore, there are several small projects of self-generation and distributed generation throughout the country, some in operation and others under construction, with a potential installed capacity of 1025 MW [19].

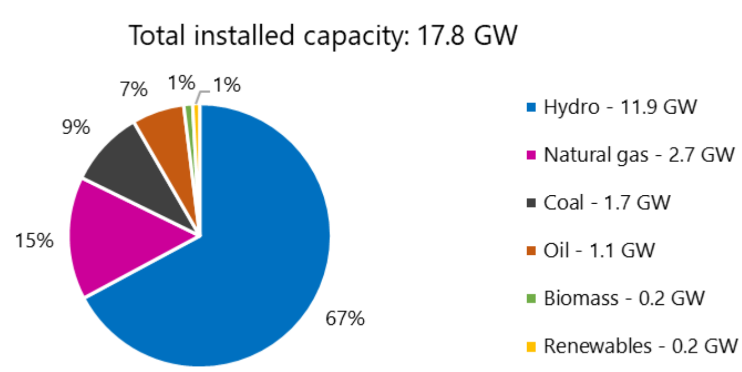

Figure 2. Power installed capacity in Colombia 2021 [18]

The transport sector constitutes the largest consumer of energy (Figure 3), accounting for 38% of the total energy consumption. The industrial sector is the second largest energy consumer, wherein energy is predominantly employed for direct and indirect heat supply, utilizing diverse resources such as bagasse, coal, and natural gas.. The residential sector primarily relies on wood for rural demand, while urban households use electricity and natural gas. The commercial and public sectors are the fourth significant consumers of energy, relying mainly on electricity, LPG, and natural gas. Mining and other sectors account for the remaining 10%.

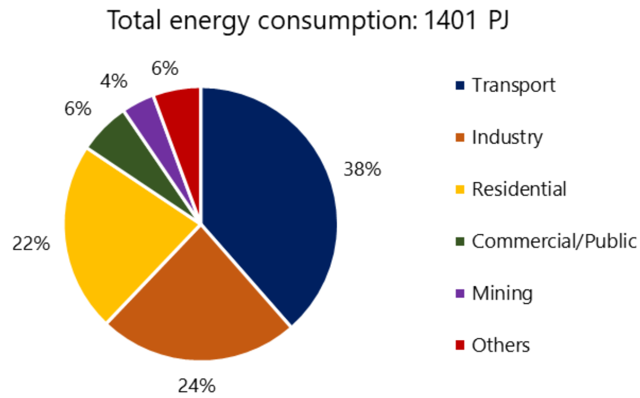

Figure 3. Energy consumption by sector in 2021 [17]

According to the latest national inventory of GHG emissions, energy accounted for one-third of the net GHG emissions in Colombia, making it the second-highest emitter after the Agriculture, Forestry, and Other Land Use (AFOLU) sector [1]. Energy-related emissions have increased by approximately 3% annually since 1990 (Figure 4). The average distribution of emission flows is composed of CO_2 (88.9%), CH_4 (9.9%), and N_2O (1.2%), highlighting the strong dependence on fossil fuels in Colombia's end-use energy and the significant challenge for decarbonization moving forward.

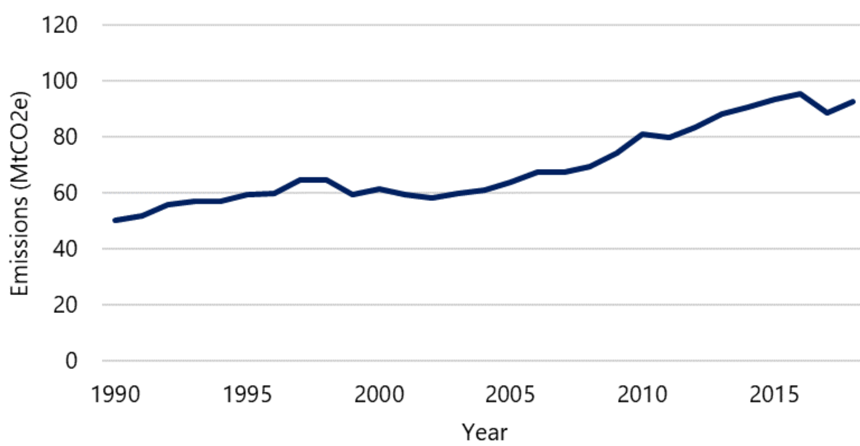

Figure 4. Energy GHG emissions in Colombia [1]

1.2. Literature review

Different studies have investigated the strategies of GHG emissions mitigation and energy transition for the Colombian energy system using mathematical modelling. Cadena and Haurie evaluated the implications of abatement measures derived from the Kyoto Protocol for the Colombian economy using the MARKAL model [20]. Recent works have explored the actions needed to comply with the goals of the Paris Agreement. Arango-Aramburo et al. used the LEAP model to quantify 4.41 $MtCO_2e$ of emissions prevented by 2040 by implementing two NAMA's focused on replacing low-efficiency refrigerators and supplying renewable energy for communities non-connected to the grid [21]. National government also used the LEAP tool for the NDC formulation [22] and the national energy plan evaluation (NEP) [16]. The NEP defined in its most ambitious scenario that a 27% reduction in fossil fuel end-use by 2050 would result in a decrease of 20 MtCO2e and investments equal to 532 billion of US$.

The decarbonization of the power sector have received much attention as a measure to provide clean energy and secure sustainability in the energy system. Pupo-Roncallo et al. analyzed the impacts of large-scale integration of variable renewable energy sources in future power scenarios using the ENERGYPLAN model [23]. They estimated that the maximum technical penetration levels of wind and solar power by 2030 were 22% and 11%, respectively. In the same line, Benavides et al. determined that a fast decarbonization of the power system by 2030 would cost more than 40 billion of US$, although they did not provide details of the modelling approach [24]. In addition to simulation modelling, other authors have used integrated assessment models (IAMs) to consider the AFOLU, industrial processes and waste sectors. For instance, the GCAM model was used to evaluate the deep decarbonization pathways to 2050 compatible with the Paris agreement, demonstrating that energy efficiency, bioenergy and clean electricity are three primary means to achieve the decarbonization of the Colombian energy system [25]. Arguello et al. carried out a cost-benefit analysis of sectoral transformations to reach carbon neutrality by 2050 and found that a mitigation scenario brings more operational savings and socioeconomic benefits than a reference scenario, however, there are no details of the model implemented [26]. Moreover, IAMs along with macroeconomic models were utilized to assess the effect of carbon taxes and abatement targets in the reduction of CO_2 emissions in the energy sector in Colombia [27]. As result, the study showed that wind, bioenergy with CCS (BECCS), and fossil fuels with CCS enabled emission reductions under different schemes of CO_2 taxes and abatement targets. Nevertheless, there are no details in the sectoral impacts of these energy transformations.

The role of bioenergy to achieve the low-carbon ambition by mid-century in Colombia is part of additional research efforts in the past years. Gonzalez-Salazar et al. proposed a modelling framework to evaluate the accelerated bioenergy deployment in Colombia by 2030 considering the energy, economy, emissions, and land use nexus [28]. The results indicate that the development of bioenergy should prioritize the deployment of technologies for bio-methane production, power generation and cogeneration, although emission reduction would not be significant (less than 10%) compared to the baseline. The potential of bioenergy in the long-term was also explored by Younis et al. using the TIMES model, showing that biomass might supply 315 and 760 PJ/year for energy and chemical sectors respectively [29]. Other institutions have explored hydrogen for energy end-uses as this energy carrier has gained momentum in the last two years; however, more open information in the modelling approaches is still required [30,31]. As we can see, the previous works have been based on simulation, IAMs, and macroeconomic models with few uses of ESOM. None of them has also applied open modelling and the U4RIA principles, with even some black box studies. This paper bridges this knowledge gap by providing Colombia's first open tool for integrated energy planning. The research also contributes to assessing decarbonization pathways, providing quantitative insights for policymakers and stakeholders. These results can potentially be leveraged to secure concessionary financing, replicating the Data-to-Deal pipeline developed in Costa Rica [14].

2. Methodology

2.1. The OSeMOSYS-COL model

We conducted a systematic literature review to analyze the principal energy system optimization modelling frameworks and their suitability for integrated evaluation of decarbonization pathways [32]. As a result, we found that the Open Source Energy Modelling System (OSeMOSYS) framework is recognized as the most advanced open tool for the energy policy community [11]. OSeMOSYS is designed to be fully accessible, straightforward, and transparent for supporting long-term energy modelling in academia, industry, and governments [13,33–35]. The framework has widely been used to support local [36–38], national [9,39–49], and regional [50–52] energy system assessments.

Considering the high-quality features as the open-source modelling framework and the wide range of applied studies implementing the tool, we chose OSeMOSYS to carry out the present paper. Full documentation of OSeMOSYS basics is available at [53]. The OSeMOSY-COL represents the first version of a full open-source model for supporting the integrated energy planning in Colombia. It is a bottom-up linear programming model which finds the optimum energy-technology mix evolution, guaranteeing the minimum cost, GHG emission limits, and the satisfaction of all energy demands. OSeMOSYS-COL is a Python-based model and is available at the Zenodo repository of the supplementary material [54]. Further information of the model can be found in the GitHub repository of OSeMOSYS [55].

2.1.1. Reference Energy System (RES)

The Colombian energy system is modelled as a macro-system representing the whole chain from the primary sources to the end-uses, including 169 technologies and 77 commodities, with a yearly time resolution and a single-node spatial resolution. A simplified version of the reference energy system is presented in Figure 5. The primary sources encompass domestic renewable energy potentials, uranium, fossil fuel reserves and biomass resources. We include liquified natural gas (LNG) imports, crude oil, and petroleum derivatives. Energy carriers (e.g., natural gas or coal) can be used directly to supply final services (e.g., direct heat or cooking), and can also be transformed into secondary commodities such as electricity or hydrogen. Energy exports are not considered due to a lack of information about future market demand and international agreements.

Fossil fuel and renewable energy power plants are included, and CCS is available for thermal generation (coal and natural gas with CCS) and bioenergy (BECCS). Power transmission and distribution are represented through technologies to capture the capacities and costs of expansion in the Interconnected National System (INS) [56]. For non-interconnected zones (NIZ), decentralized energy options are modelled. Natural gas and crude oil are processed through refineries, regasification, and liquified petroleum gas (LPG) plants. We also model biofuel production, including distilleries, biodiesel plants and blending processes. Hydrogen production encompasses steam methane reforming (SMR) and electrolysis. Transport and distribution of natural gas, coal, LPG, hydrogen, and biofuels are modelled. For the mobility sector, recharging stations and hydrogen refuelling stations are included. It is assumed that biomass will be utilized on-site, in proximity to the production location; thus, transportation and distribution are not considered.

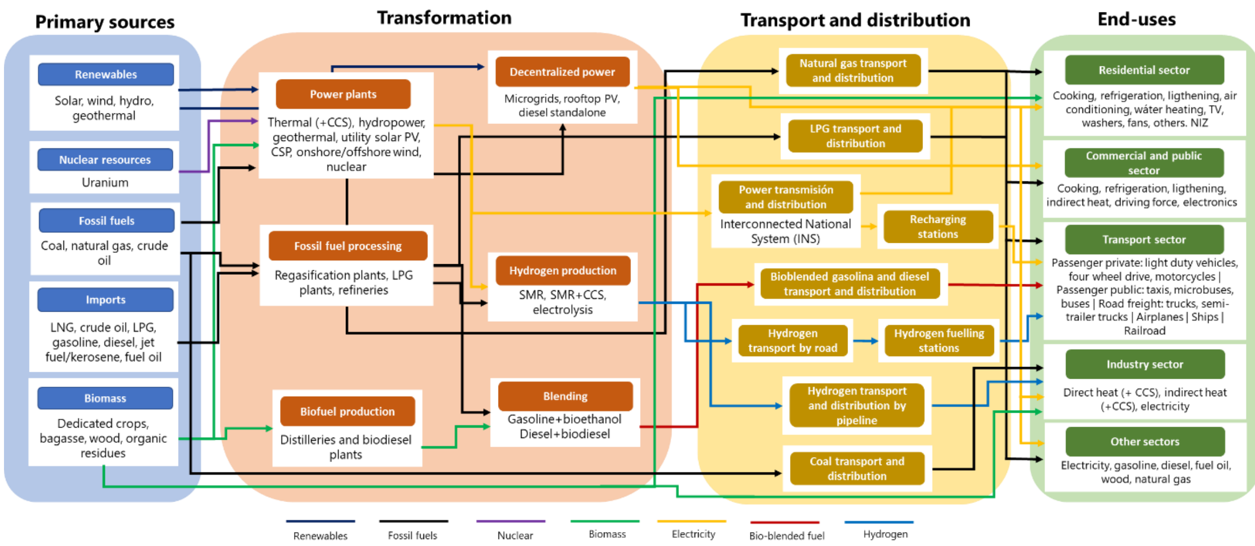

Figure 5. Simplified reference energy system

Four larger consumer sectors are represented in detail (i.e., transport, industry, residential, commercial and public). The end-uses in the residential sector are the principal household services such as cooking, refrigeration, and lighting. The electrification demand in NIZ is modelled considering the objective of universal power access by 2030 [57]. The commercial and public sector covers demands for cooking, direct heat, refrigeration, and lighting, among others. The transport sector is divided into the different modes of transportation (i.e., road, air, water, and rail). Road transport accounts for 90 per cent of transport energy demand (UPME, 2021a). It is disaggregated into passenger private transport, passenger public transport, and freight transport using available technologies such as internal combustion engine vehicles (ICE), battery electrical vehicles (BEV), plug-in hybrid vehicles (PHEV), and fuel cell electrical vehicles (FCEV). The industry sector is diverse and was simplified via heat (i.e., indirect and direct heat) and electricity demands. The heat generation can be supplied by biomass (including BECSS), coal and natural gas (with or without CCS), electricity and hydrogen. The other sectors were grouped into single commodity demands (firewood, natural gas, electricity, fuel oil, gasoline and diesel) to account for the rest of the national energy balance. The complete list of technologies can be found in [58].

2.1.2. Demand projections

The modelling approach represents end-use demands instead of energy carrier demands, enabling the selection between different energy alternatives (e.g., we represent energy demand for cooking service and not natural gas demand for cooking). The baseline 2021 end-use demands are obtained from the national useful energy balance reported by the Mining and Energy Planning Unit - UPME [59]. The gross domestic product (GDP) is used to project the demands, considering the expected value for 2022 in 8 percent due to COVID-19 pandemic rebound [60], and a value of 3.2 percent per year for the period 2023-2050 based on the average GDP observed in the period 2012-2019 [61]. Table 1 summarizes the end-use demands used as exogenous parameters for the model. Yearly information on the demand time series is available at [58].

Table 1. End-use demands

Sector/Unit	End-use demand	2021	2030	2040	2050
Industry (PJ)	Direct heat	72.2	100.3	137.4	188.3
	Indirect heat	89.4	124.3	170.3	233.3
	Driving force	27.6	38.4	52.6	72.1
Residential (PJ)	Cooking	37.2	51.7	70.8	97.0
	Refrigeration	5.4	7.5	10.2	14.0
	Lightening	0.8	1.2	1.6	2.2
	Air conditioning	2.3	3.2	4.4	6.0
	Water heating	3.1	4.3	5.8	8.0
	TV	1.8	2.5	3.4	4.6
	Washer	0.2	0.3	0.4	0.5
	Fan	1.5	2.1	2.9	4.0
	Other electronics	3.0	4.1	5.6	7.7
	NIZ	1.7	5.9	8.1	11.1
Transport (Gpkm) or (Gtkm)	Light duty vehicle transport	32.9	45.7	62.6	85.8
	Four-wheel drive transport	9.5	13.1	18.0	24.7
	Motorcycle transport	87.1	121.0	165.8	227.2
	Taxi transport	27.3	37.9	52.0	71.2

	Microbus transport	148.8	206.8	283.4	388.3
	Bus transport	341.9	475.1	650.9	891.9
	Truck freight	47.8	66.5	91.1	124.8
	Semi-trailer truck freight	81.1	112.7	154.4	211.6
	Air transport	23.1	32.1	44.0	60.3
	Maritime transport	15.7	21.8	29.9	40.9
	Railroad transport	37.4	52.0	71.3	97.7
Commercial and public (PJ)	Cooking	3.2	4.4	6.0	8.2
	Indirect heat	7.8	10.9	14.9	20.4
	Air conditioning	2.0	2.8	3.8	5.2
	Refrigeration	7.1	9.9	13.6	18.6
	Lightening	1.7	2.3	3.2	4.4
	Electronics	1.9	2.7	3.7	5.1
Other sectors (PJ)	Natural gas demand	9.4	13.1	17.9	24.5
	Firewood demand	12.7	17.6	24.2	33.1
	Diesel demand	61.7	85.7	117.5	161.0
	Electricity demand	40.9	56.8	77.9	106.7
	Fuel oil demand	5.8	8.1	11.0	15.1
	Gasoline demand	2.3	3.2	4.4	6.0
	LPG demand	5.3	7.4	10.1	13.8

End-use demands are calculated in PJ except for the transport sector. Transport demands are calculated using data of energy consumption of the different fuels, efficiencies, and load factors for passenger or freight mobility technologies. Energy consumption data by vehicle type is taken from [59], and efficiencies and load factors come from [62,63]. Detailed information of the calculations and assumptions in the transport sector is reported by [58]. In addition, there are no available characterizations of the remaining sectors (e.g., agriculture or mining sectors); therefore, it is assumed no intervention in these sectors and a proportional mix of the energy carriers in the modelling horizon.

2.1.3. Techno-economic input data

Techno-economic data include costs, installed capacities, emission factors, efficiencies, operational lifetimes, and capacity factors. Capital costs represent overnight costs and O&M costs reflect non-fuel variable costs and fixed costs related to the operation and maintenance of the technologies. The fuel variable costs account for the primary energy technologies (i.e., domestic production and imports). Learning rates of cost data are not calculated endogenously, but the decreasing trend of capital and variable costs are included using literature projections. As CO_2 infrastructure is not explicitly modelled, there is a variable cost of transport and storage of CO_2 equal to 36.1 US$/t added to CCS technologies [64]. The estimated geological storage capacity of CO_2 is 360 Mt based on [65]. Detailed cost data and considerations for cost estimations is described by [58].

The installed capacities in the power sector were obtained from the market operator XM for centralized generation [18], and from the Promotion and Planning Institute for Energy Solutions (IPSE) regarding the decentralized energy [66]. Fossil fuel processing and refining capacities are derived from UPME [67]. Transport and distribution capacities depend on the energy carrier and are depicted by [58]. On the demand side, the residual capacities are estimated using the energy consumptions in the base year 2021 and previous sectoral studies [62,68,69]. Guidelines for the estimation of residual capacities are described by [58].

Planned power plants are included, considering the capacity allocated in the renewable energy auctions and other projects with contracts committed. The first auction in 2019 awarded 1298 MW [70], and the second version in 2021 allocated 796 MW [71], among solar and onshore wind projects. The Hidroituango project is assumed to provide 600 MW per year in the period 2023-2026, and other power plants are progressively incorporated according to the latest report of UPME [72]. Phase-out power plants are not yet included due to information unavailability. For demand-side technologies, simplified mortality lines are assumed (i.e., residual capacity decreases linearly based on its operational life). Further explanation of residual capacity assumptions is provided by [58]. Operational lifetime involves standard values of technology life, and no refurbishment or retrofitting is considered.

The emission factors are expressed in CO_2 equivalent, including the emissions of CO_2, CH_4 and NO_2 [22]. Fugitive emissions from fossil fuel processes are not considered. Efficiency of capture for CCS technologies is set at 90% of CO_2 emissions [64]. The average capacity factors of renewable power technologies are estimated using the generation and capacity information from 2015-2021 [73]. The capacity factors for other supply and demand technologies are based on available data from institutions such as the International Energy Agency or the European Joint Center of Research. Technology efficiencies are also extracted from a thorough literature review considering diverse sources. Capacity factors and efficiencies are considered constant during the whole period of modelling. Detailed data of emissions, capacity factors and efficiencies is available at [58].

2.1.4. Energy source availability and import costs

Primary resources can be divided into fossil fuel, nuclear, biomass and renewable energy. Fossil fuels and nuclear minerals are finite energy sources (nuclear fusion is not considered here), thus, national reserves give their availability. Biomass and renewable energy are partially infinite resources; hence their availability is reported by annual potential. For renewable energy, the estimated potential is based on the expected maximum installed capacity for power generation. The effect of climate variables in renewable power generation is not explicitly modelled due to the yearly resolution; nevertheless, conservative capacity factors are used. Table 2 summarizes the energy availability per energy resource.

Table 2. Energy availability per source

Category	Resource	Unit	Availability	Reference
Fossil fuels	Crude oil[a]	Mb	5704	[74]
	Natural gas[b]	Tcf	10.9	[75]
	Coal	Mt	1586	[76]
Nuclear	Uranium	kt	11	[77]
Renewable energy	Hydro (dam)	GW	51.2	[29]
	Hydro (run-of-river)	GW	27.8	
	Solar PV	GW	8172.2	[78]
	Solar CSP[c]	GW	17	Estimated
	Onshore wind	GW	35.2	[78]
	Offshore wind	GW	50	[79]
	Geothermal	GW	1.2	[80]
Biomass	Sugarcane (for bioetanol)	PJ/year	573	[29]
	Oilpalm (for biodiesel)	PJ/year	315.5	
	Bagasse	PJ/year	166.5	
	Firewood	PJ/year	260	
	Agriculture and forestal residues	PJ/year	165	

[a] Intermediate scenario is used to consider future additions of crude oil reserves based on historical exploration success rates
[b] Intermediate scenario is used to consider future additions of natural gas reserves based on historical exploration success rates
[c] There is no available data about the potential for CSP in Colombia, whereby an estimation of 17 GW is assumed considering the same installed power plant capacity in 2021.

The fossil fuel production per year is limited with caps using the maximum production levels in the period 2010-2021, following 91.2 Mton/year for coal [81], 368 Mb/year for crude oil, and 456 Gcf/year for natural gas [82]. As exports are not considered in the model, the available crude oil reserves are adjusted, assuming 50% of crude oil for exports, based on the ratios in 2015-2021 [17]. Import options include LNG, crude oil, and petroleum derivatives. There are no considerations of coal imports due to the ratio of reserves/production implies self-sufficiency for more than 50 years [76]. The costs of fossil fuel imports are obtained from projections performed by UPME in the period 2021-2037 under the reference scenario, including the effect of the Ukraine-Russia conflict [83]. For 2038-2050, the data is extrapolated based on a linear trend. Table 3 illustrates the cost behavior in critical years. Domestic production costs of the primary energy resources are assumed constant for the modelling horizon. Further cost detailed data is available at [58].

Table 3. Fossil fuel costs (imports)

Energy carrier	Price (USD/MBTU)			
	2021	2030	2040	2050
Natural gas (LNG)	4.72	9.04	11.95	15.23
Crude oil	9.92	13.61	15.36	17.28
Diesel	9.15	9.14	11.21	13.5
Gasoline	10.65	11.65	15.75	20.2
LPG	12.7	23.54	32.36	42.08
Fuel oil	8.9	14	18.01	22.4
Kerosene/Jet Fuel	14.75	24.68	32.87	41.8

Source: Adapted from [83]

2.1.5. Socioeconomic considerations

We use a discount rate of 6.4% based on the last NEP [16]. Apart from the investment and operating costs of technologies described in section 2.1.3., OSeMOSYS-COL includes carbon taxes and externality costs. A carbon tax is estimated from the last update of fiscal reform in 2022. The law establishes a progressive growth linked to the consumer price index plus one percent point until reaching the value of three tributary value units (UVT) [84]. Based on the current carbon tax and UVT value, we estimated a linear growth from US$5 per tCO_2 in 2021 to US$30 per tCO_2 by 2050. The externalities comprise local air pollution and global warming costs based on [85,86]. Local air pollution externality expresses the monetary cost of premature cardiovascular and pulmonary diseases caused by fossil-fuel particulate material. Global warming externality estimates the cost of environmental damages associated with climate change (e.g., loss of crops, infrastructure affected by floodings, forest fires, water scarcity). Table 4 presents the externality costs used within the study. For jet fuel/kerosene, diesel values are used, and for LPG, the values of natural gas are used considering the most similar chemical composition.

Table 4. Externality costs by fuel

Fuel	Global warming	Local pollution	Unit
Gasoline	0.111	0.050	US$ per liter
Diesel	0.127	0.714	US$ per liter
Jet fuel/Kerosene	0.127	0.714	US$ per liter
Coal	4.370	3.260	US$ per GJ
Natural Gas	2.586	0.179	US$ per GJ
LPG	2.586	0.179	US$ per GJ

Source: Adapted from [86]

2.1.6. Model calibration

Since ESOMs cannot be appropriately validated [87], the models are calibrated by checking the consistency of model results concerning a past or present state using a reference year [88]. Our calibration year was 2021. We compared the model results and the end-use energy reported by the Colombian energy balance in 2021 [17], obtaining an acceptable error of 1.9%, as illustrated by Figure 6. Regarding energy production, the fitting was also reasonable, with a relative error of 1.5% (See supplementary material). The significant differences are due to unbalance of bioethanol-gasoline and biodiesel-diesel because the model assumes a constant blending percentage (8% for bioethanol and 10% for biodiesel), but the country has different percentages depending on the region. We also compared the results of GHG emissions, where the model outcome was 81.1 $MtCO_2e$ and the reference value was 85 $MtCO_2e$ [89], representing a relative error of 4.6%.

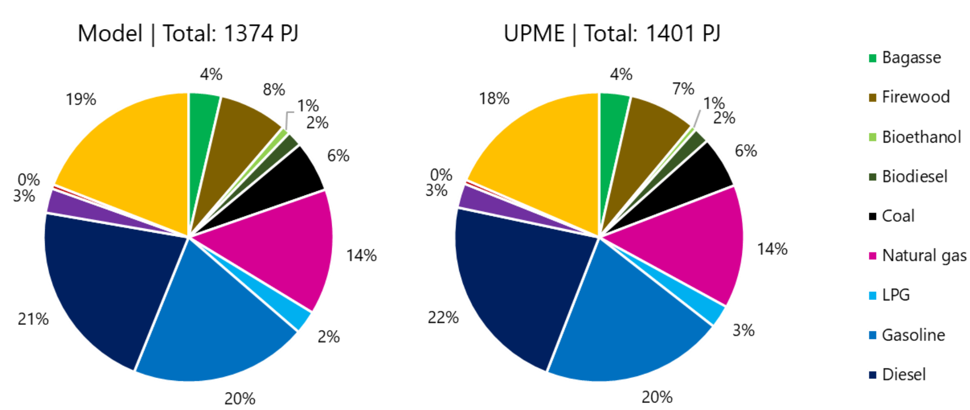

Figure 6. Model results versus real end-use energy in 2021

2.2. Scenario analysis

We evaluated three scenarios: the Business-As-Usual scenario (BAU), the Decarbonization Pathway scenario (DPS), and the Alternative Decarbonization Pathway Scenario (ADPS). Table 5 summarizes the principal features of the scenarios.

- The BAU scenario is a baseline scenario that explores the least cost trajectory, considering the same technologies and conditions of the past years. The BAU scenario involves a low penetration of new technologies (e.g., hydrogen, CCS, BEV, FCEV), no emission caps, and use of energy carriers based on historic trends.
- The DPS scenario stablishes the target to accomplish the NDC 2020, reducing the GHG emissions in the energy sector by 20% by 2030 [4], and achieving a 90% reduction by 2050. According to the Long-Term Strategy, the remaining 10% of energy-related emissions is expected

to be compensated by AFOLU sector [90]. In the DPS scenario, all technologies are not constrained to explore their role in the future decarbonized energy system.

- The ADPS scenario assumes there is no deployment of CCS technologies and the target of GHG emissions mitigation is 15% by 2050. The rationale behind the reduction in the emissions limit stems from the lack of decarbonization alternatives for air and maritime transportation in the model. Accordingly, achieving reduced levels of GHG is unattainable without resorting to negative emissions derived from BECCS.

Table 5. Scenarios used in the study.

Scenario	Explanation	Rationale	Key values	Code
Business-as-usual	This scenario represents a baseline scenario to compare it with other scenarios	The changes on the demand side represent large transformations and there are no significant policies to modify the current energy system currently	Demand is supplied keeping the same proportions of current technologies	BAU
Decarbonization pathway	This scenario represents the most cost-efficient pathway to accomplish the targets of NDC 2020	Availability of domestic reserves of coal and natural gas, and potential to develop bioenergy make CCS an attractive option to enable those resources in a low-carbon economy [91]	CCS technologies are available from 2030. Emissions limit by 2050: 7 $MtCO_2e$	DPS
Alternative decarbonization pathway	This scenario represents the sensitivity of a decarbonization pathway in case of CCS technologies are not available	CCS has barriers in terms of technology maturity, geological capacity of storage, and social acceptance [92]	CCS are not available. Emissions limit by 2050: 10.25 $MtCO_2e$	ADPS

There are some additional considerations included in all the scenarios. Each technology has a technology penetration rate equivalent to 44 PJ/year of new installed capacity. The penetration rate was estimated considering Colombia's average annual energy increase consumption in the last 10 years [17], and is introduced to smooth the expansion of new technologies. In the power sector, coal and natural gas decrease electricity generation progressively reaching zero by 2040 and 2045 respectively based on the LTS [90]. In the residential sector, the use of firewood for cooking decreases linearly to reach a maximum of 10% by 2050 [93]. In the transport sector, BEVs in the cargo segment are available from 2030, and FCEVs are available from 2030 for all the services [92]. In the industry sector, hydrogen-fueled technologies for heat generation are available from 2030 [94]. It is assumed that services in other sectors are electrified for DPS and ADPS scenarios, and the demand for non-electricity commodities decreased linearly to 25% by 2050.

3. Results

We present here the results starting with GHG emissions, energy consumption, the transformations in the different sectors, and finishing with the socioeconomic assessment.

3.1. GHG emissions

In the BAU scenario, demand technologies continue to use fossil fuels in the current proportions, and the GHG emissions grow steadily reaching 177.3 $MtCO_2e$ by 2050, more than the double compared to 2021. The carbon budget derived from the NDC 2020 is satisfied by the DPS scenario achieving a target of 7 $MtCO_2e$ by 2050. The BECCS technologies in the power and industry sectors yield negative emissions of around 12 $MtCO_2e$ per year, compensating non-abatable emissions in other sectors (e.g., air, maritime and minor sectors). The negative emissions balance also enables maintaining some fossil fuel uses prone to be decarbonized, especially in road transport and commercial and public services. In the ADPS scenario, the emissions target is placed at 10.25 $MtCO_2e$, as described in section 2.2. Without CCS technologies, industry sector delays its decarbonization process and transport sector must make a greater effort to cut almost 34 $MtCO_2e$. Figure 7 presents a comparison of the emissions trajectories for each scenario. The mitigated GHG emissions contribute to reduce the carbon intensity moving from 51.2 $ktCO_2e/PJ$ in the BAU scenario to 3.3 $ktCO_2e/PJ$ in the DPS scenario and 5.3 $ktCO_2e/PJ$ in the ADPS scenario.

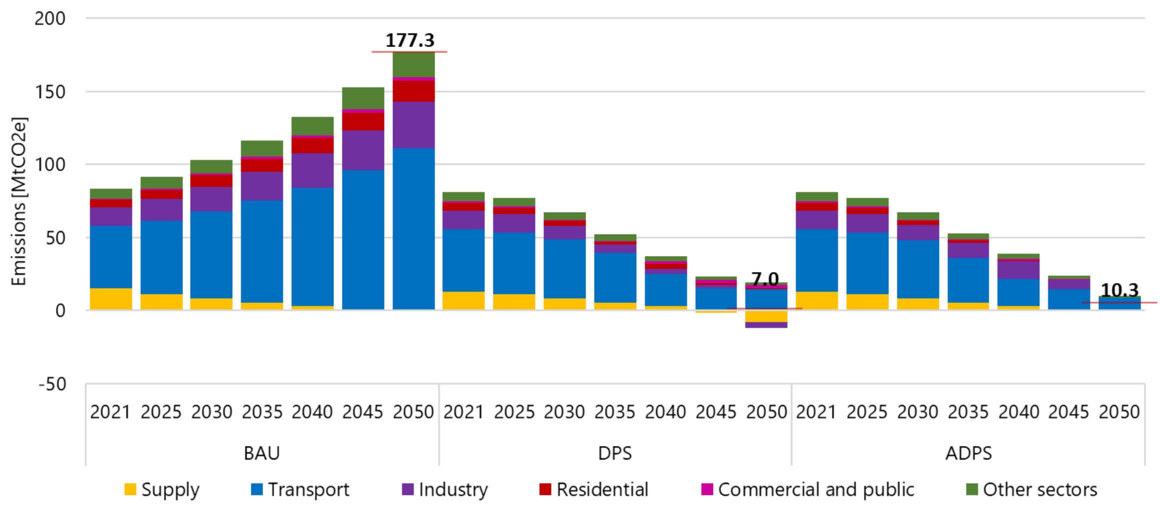

Figure 7. Annual GHG emissions by sector

3.2. Energy consumption

The BAU scenario's energy consumption reaches 3463.5 PJ by 2050, representing 2.5 times the energy used in 2021. The decarbonization pathways satisfy the end-use demands with less energy compared to the BAU scenario. The DPS scenario requires 2116.1 PJ by 2050 and the ADPS scenario demands 1941.1 PJ by 2050. The penetration of more efficient technologies on the supply and demand sides enables lower energy requirements in the decarbonization scenarios and improved energy intensity. The energy consumption transforms to achieve GHG emissions reduction as illustrated in Figure 8. The BAU scenario continues the trend of a high dependency on fossil fuels with around 70% of total energy. The decarbonization scenarios present four facts to be highlighted:

- The electrification of end-uses dominates the energy transition. The participation of electricity grows from 19% in 2021 to 54% in 2050 for the DPS scenario, and to 69% in 2050 for the ADPS scenario.
- Natural gas can support the energy transition when CCS technologies are available. In the DPS scenario, natural gas will increase from 14% to 27% by 2050, becoming the second largest energy carrier.
- Without CCS technologies, hydrogen is key to accomplishing the GHG mitigation targets. The ADPS scenario shows an increase of hydrogen's share from 0% to 15% by 2050.
- The use of coal will disappear by 2050, and petroleum derivatives share will decrease progressively until levels of 10% by 2050.

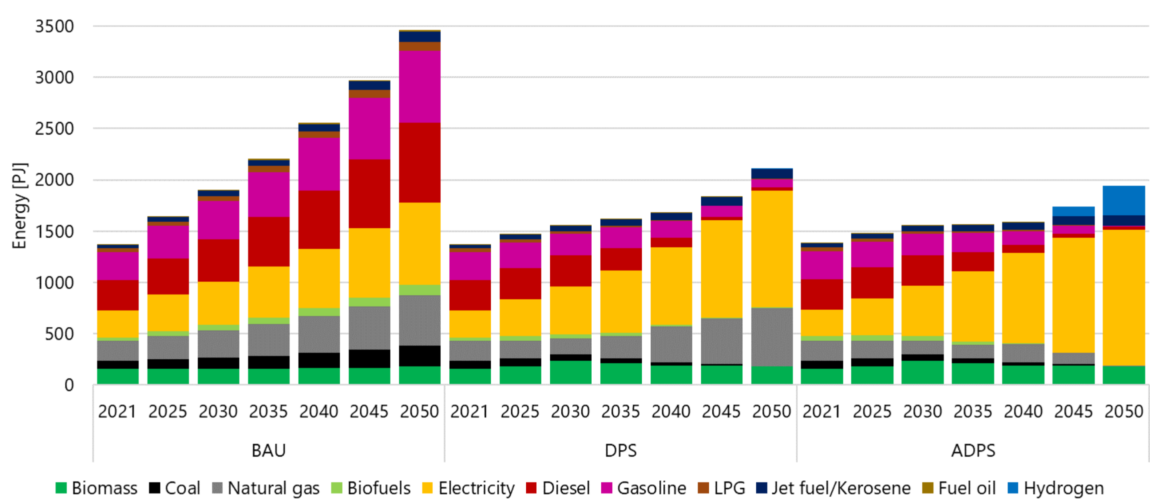

Figure 8. Final energy consumption 2021-2050 by fuel

Energy self-sufficiency is crucial to guarantee a solid and secure energy transition, and energy imports play a relevant role considering the risk associated with energy dependency on external sources. The BAU scenario shows that the continuous use of fossil fuels will increase energy imports as oil and natural gas reserves will not be enough to support the increasing demand. The fossil fuel imports will grow from

6% to 60% of the total energy by 2050 in the BAU scenario, as illustrated in Figure 9. Gasoline and diesel for the transport sector are the principal imported fuels, representing 43% of the energy mix by 2050. On the other hand, the decarbonization pathways smooth the requirements of imported energy. The imports are 7% of total energy by 2050 in the DPS scenario (gasoline and jet fuel) and 6% of total energy by 2050 in the ADPS scenario (diesel and jet fuel).

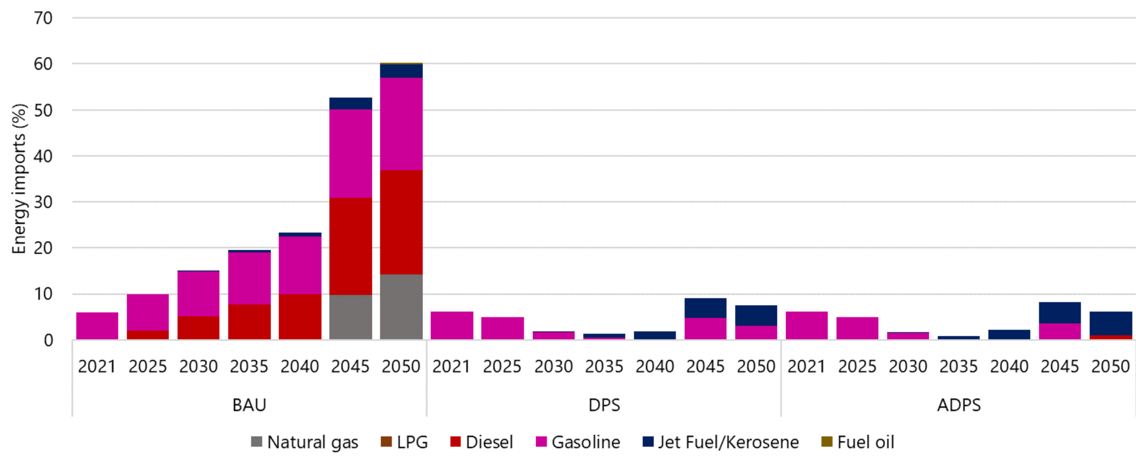

Figure 9. Energy imports by fuel as percentage of total energy

3.3. Technology deployment

Power generation capacity increases in all the scenarios moving from 89.5 GW in the BAU case to 127.3 GW in the DPS scenario and 169.8 GW in the ADPS scenario, as depicted by Figure 10. As we described previously, the electrification of new end-uses boosts the utilization of electricity as energy carrier in all sectors. The efforts to decarbonize the national energy system will imply multiplying the current power capacity between eight and ten times by 2050. In the DPS scenario, CCS technologies reduce the need to electrify some final services, essentially in the industry sector, translating into a 50 GW reduced installed capacity by 2050. For both BAU and DPS scenario, the new installed capacity is based on onshore wind and solar utility, reaching 69.1 GW and 98.7 GW, respectively. In the case of the ADPS scenario, these renewable sources dominate the growth with 111.5 GW, however, after 2040 there is a high diversification of the power capacity, including offshore wind, CPS, and nuclear technologies (18.1 GW altogether). Hydro capacity also increases in the ADPS scenario significantly, reaching 45.6 GW.

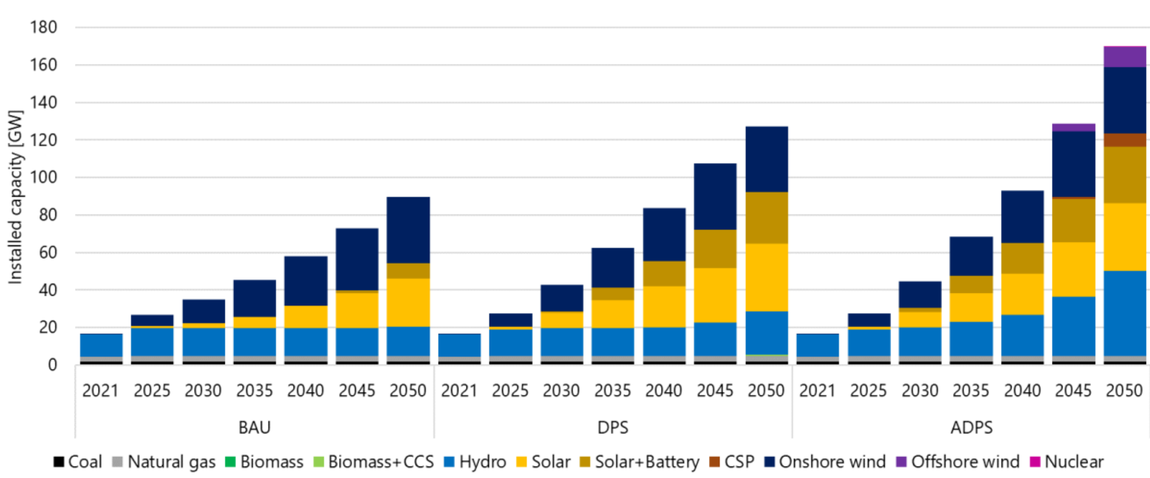

Figure 10. Installed power capacity by technology.

Decarbonizing the national energy system would require profound transformations across all demand-side sectors. Figure 11 summarizes the technological changes through scenarios for the transport, industry, residential, and commercial and public sectors. In the transport sector, the road vehicle fleet is progressively electrified, resulting in over 95% of total demand by 2050 being met by BEV and PHEV. Hydrogen-fueled vehicles complement the public passenger demand in the bus category in the 2040s. In the industrial sector, natural gas furnaces and boiler with CCS dominate the heat demand, meeting 77% of total demand by 2050 in the DPS scenario. Biomass, with and without CCS, completes the heat demand under the DPS scenario. In the ADPS scenario, the direct and indirect heat demands are met by a combination of hydrogen, electric and biomass technologies by 2050.

In the residential sector, natural gas and LPG stoves are entirely replaced by electric stoves by 2050 in both scenarios. Water heating is supplied by natural gas in the DPS scenario and by electricity in the ADPS scenario. In the commercial and public sector, natural gas and electricity will supply the demands of cooking and indirect heat by 2050 in the DPS and ADPS scenarios. Low-efficiency appliances will be substituted with high-efficiency ones to enhance other end-use services such as refrigeration or lighting in both residential and commercial and public sectors in the next decade. All transformations result in efficiency improvements ranging from 2% to 20%. A detailed description of the sectoral transformations is available in the supplementary material of the article.

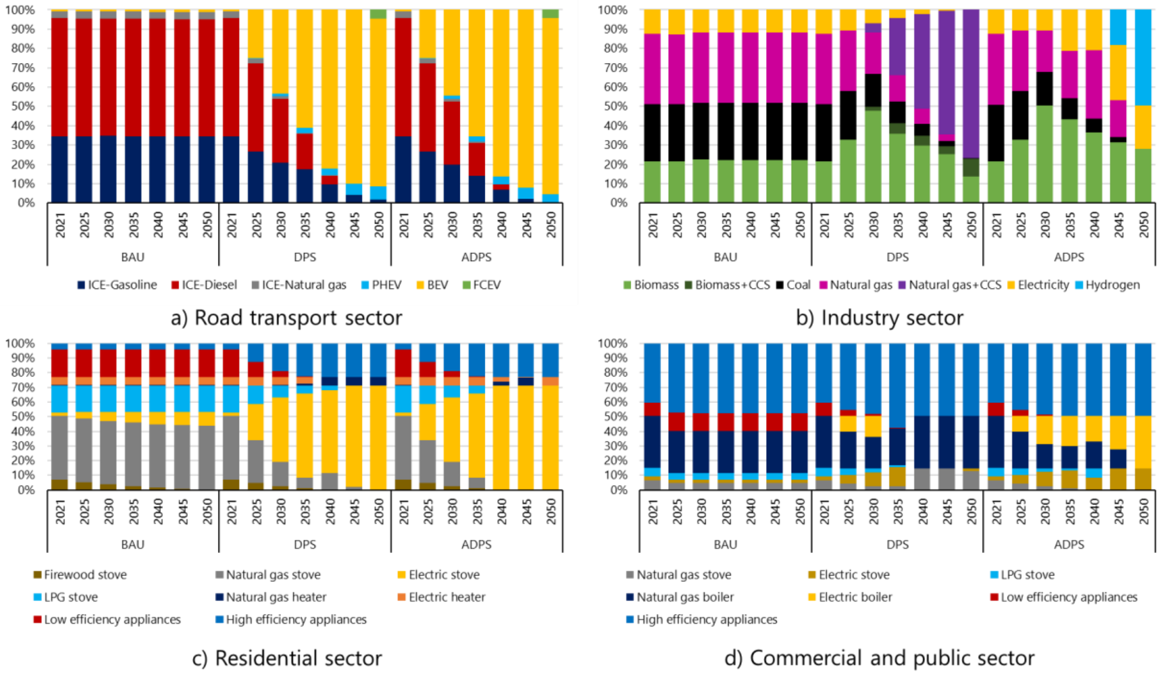

Figure 11. Distribution of sectoral demands: a) Road transport demand by vehicle technology, b) Industry heat demand by furnace and boiler fuel, c) Residential energy demand by technology, and d) Commercial and public energy demand by technology.

3.4. Socioeconomic assessment

The socioeconomic assessment considers capital cost, operational cost, carbon taxes, and externality costs. Figure 12 shows these values per scenario. The total costs (the sum of all these costs) of the BAU, DPS, and ADPS scenarios are estimated in US$1145 billion, US$1075 billion and US$1107 billion, respectively. Capital costs account for the largest share in all scenarios: US$471.2 billion, US$521 billion US$639.4 billion, respectively. The further development of disruptive technologies could lower capital costs for decarbonization pathways. The operating costs are the second largest share in all scenarios. The BAU scenario has operating costs of US$409.7 billion, and the DPS and ADPS scenarios present reduced operating costs equal to US$333.9 billion and US$324.4 billion, respectively. More than 90% of capital and operating costs in the decarbonization scenarios are associated with the deployment of electric transport (i.e., purchase and maintenance of new vehicles). A decarbonized system implies reduced GHG emissions and reduced carbon taxes correspondingly. The BAU scenario reaches carbon taxes of US$23.2 billion, while the DPS and ADPS scenarios have almost a half of the BAU amount, pointing at around US$10 billion each. A BAU scenario will also result in high externality cost (linked to health and global warming effects) of US$240 billion, whereas these costs for the DPS and ADPS scenarios are reduced: US$138.8 billion and US$133 billion, respectively.

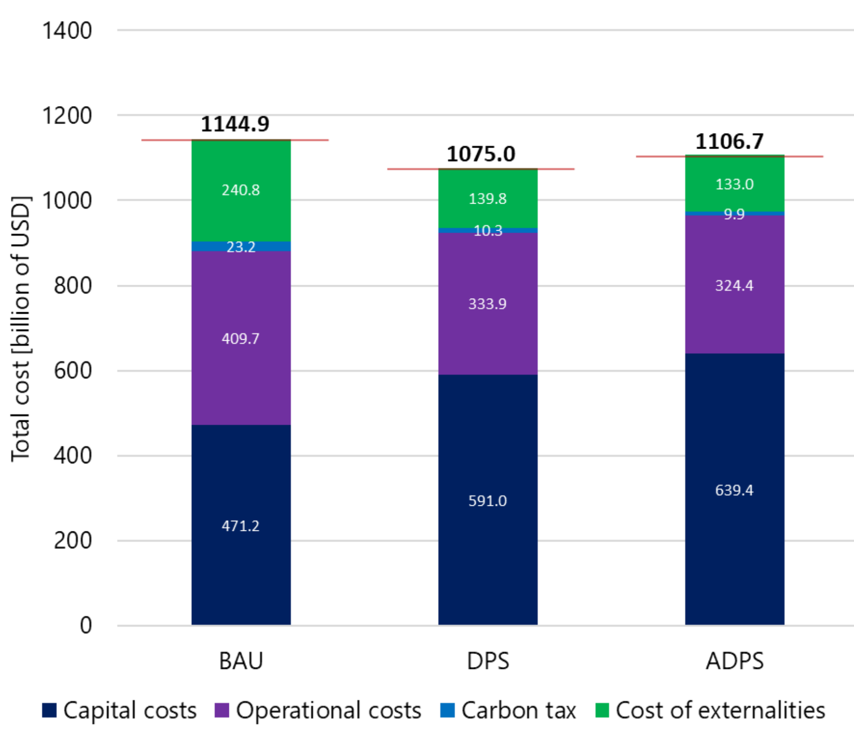

Figure 12. Cost comparison by scenario

We contrast the costs of both decarbonization scenarios with the cost of the BAU. A positive value means a net benefit and a negative the opposite. The ADPS scenario provides a net benefit of US$38.2 billion representing 11.6% of 2021 GDP, and the DPS scenario generates a net benefit of US$70 billion representing 21.2% of 2021 GDP (Figure 13). The availability of domestic biomass and fossil fuel resources coupled with CCS technologies in the DPS scenario provides almost the double of benefits compared to the ADPS scenario under the conditions of the study. In both cases, there is a clear advantage in progressing towards a carbon-neutral society to provide better air quality, fewer environmental risks, reduced extreme climate events and better quality of life for all.

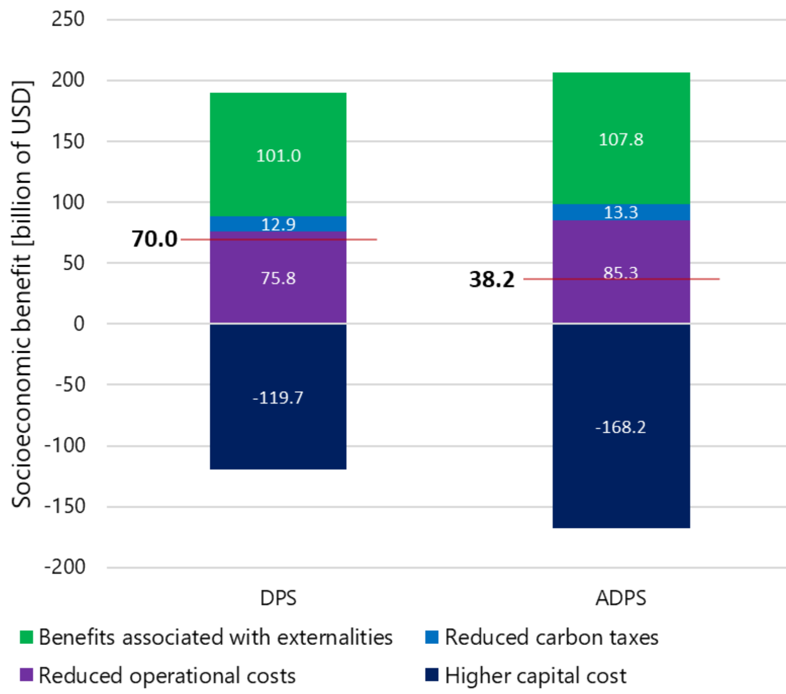

Figure 13. Socioeconomic benefits by decarbonization pathway

4. Discussion

4.1. Findings and policy insights

The study demonstrates the technical feasibility of decarbonizing the energy system in Colombia, accomplishing the NDC 2020. The energy transition will demand massive transformations through all sectors and the adoption of new technologies. Although the investment costs in the decarbonization process are more significant than the business-as-usual pathway, the savings in operational costs, carbon taxes and externalities provide greater socioeconomic benefits by mid-century. A carbon-neutral system poses additional advantages in the long-term in terms of efficiency, energy sovereignty, and GHG emissions:

- The electrification of end-uses and deployment of more efficient equipment reduces the energy requirements and improves the energy intensity by 40% compared to a fossil fuel system.
- The development of renewable resources avoids a fast depletion of crude oil and natural gas reserves, reducing future imports of fossil fuels.
- The carbon intensity could decrease by 90-95% under a decarbonization pathway.

The results demonstrate a reasonable agreement with previous studies focused on decarbonization by 2050. [25] found similar reductions in energy intensity (40%) and carbon intensity (91%) for their below 2° climate scenario. Moreover, the NEP found comparable figures in terms of costs (532 billion of US$) and reduction in energy imports (21%) for 20 $MtCO_2e$ in mitigated emissions under the most ambitious scenario [16]. Other authors are aligned with the socioeconomic benefits [26], improvement in efficiency [27], and the significance of green electrification [23] as derived from a decarbonized Colombian energy system. Table 6 shows a summary of key indicators related to the performance of each scenario.

Table 6. Comparison of performance of scenarios. All data is reported for the year 2050.

Criteria	Indicator	Scenario		
		BAU	DPS	ADPS
Efficiency	Energy intensity[a] (PJ/US$ billion)	4.20	2.57	2.35
Energy sovereignty	Percentage of imported energy over final energy (%)	60.3	7.5	6.1
GHG emissions	Carbon intensity ($ktCO_2e/PJ$)	51.18	3.31	5.28
Costs	Socioeconomic benefits (billion of US$)	-	70.0	38.2

[a] GDP was estimated at US$824.52 billion by 2050 considering the growth rate of 3.2% yearly

The materialization of a decarbonized future will require a solid integrated policy to set the regulatory incentives and mobilize financing in the next 30 years, as quick as possible. A first step in the process is establishing clear targets with temporal resolution in each sector as input to formulate the strategies and mechanisms to execute, control and verify advancement. Figure 14 gathers multiple insights derived from the results described in section 3. The contribution highlights the milestones to reach for each sector and how the evolution should occur in the timeline. The targets illustrated are indicative but a thorough discussion with stakeholders should be performed to contextualize them.

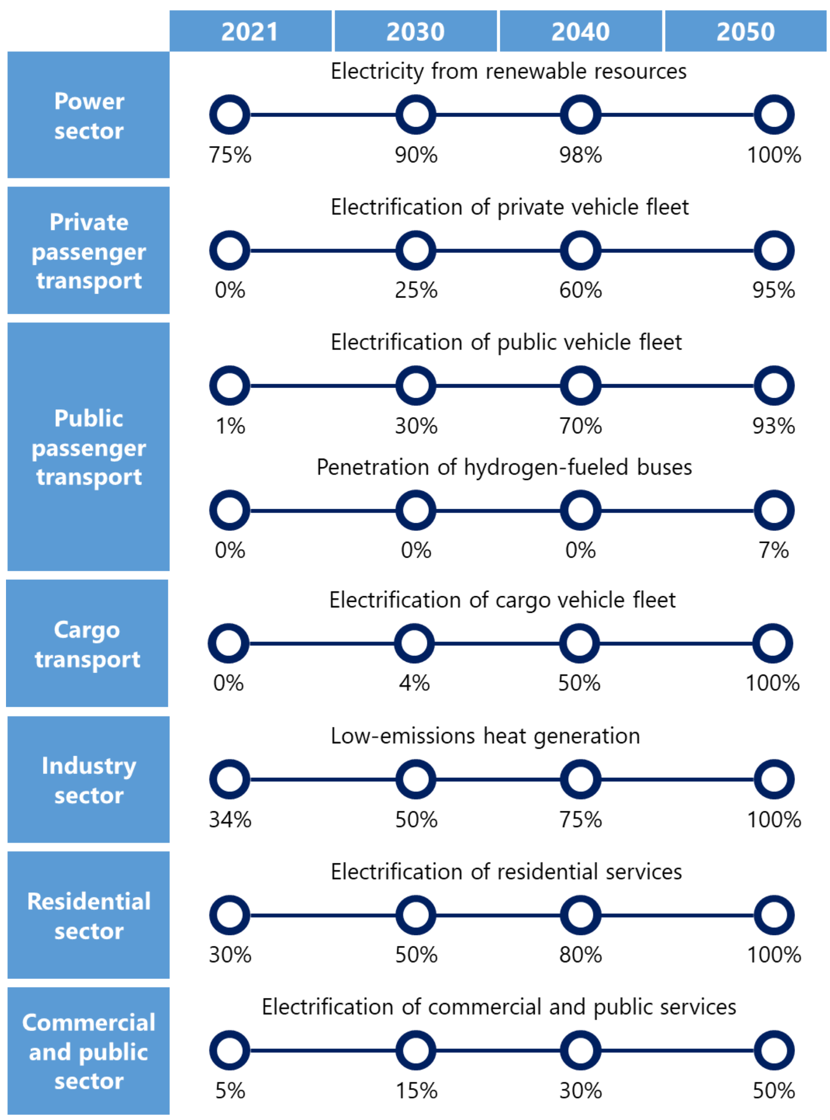

Figure 14. Sectoral targets for an effective decarbonization pathway in Colombia

The large-scale insertion of renewable power technologies is critical to assure the carbon neutrality in the life cycle of the electrified end-uses. Colombia has huge solar and wind energy potential to yield a new installed capacity rate of 2.5 to 3.5 GW per year to achieve a 100% renewable power mix by 2050. In line with [25], the future portfolio of power generation should be more diversified including rising technologies such as CPS, offshore wind, small nuclear reactors (SMR*), BECCS, and storage systems.

The electrification of the transport sector is the principal measure for decarbonization, with varying penetration levels depending on the segment. These findings align with the results of [26] who found penetrations of electricity above 80% in both passenger and cargo transport. Electric vehicles in the private passenger transport face the challenge of consumer adoption considering that 65% of vehicle fleet are motorcycles. Public passenger transport is prone to be electrified whenever recharging infrastructure is deployed. Model results show that a capacity of around 10 GW in recharging stations is required in the full-electrified transport scenario. For buses, hydrogen-fueled vehicles could support the growth of buses demand and represent 7% of public passenger demand in the decade 2040-2050, as illustrated in Figure 20. Cargo transport must surpass the technological barriers of battery energy density and long-haul autonomy to enable the electrification beyond 2030. With constraints in the penetration of electric trucks, FCEV could also be an alternative option to decarbonize the cargo transport.

For industry, there are different low-emissions options to decarbonize the heat production, including a combination of fossil fuels with CCS, BECCS, hydrogen and electricity. The enormous diversity of industrial processes will require made-to-measure strategies and specific policy designs for each case. The electrification of cooking and water heating is the clear emissions mitigation alternative in the residential sector. A regulatory building framework could provide a 25-year plan to de-escalate the use of natural gas in homes and replace it by electric appliances. Under favorable conditions of CCS deployment and natural gas reserves, there could be carbon budget to maintain the half of energy demand based on natural gas in the commercial and public sector. CCS technologies demonstrated high relevance to achieve decarbonization targets in different sectors as concluded by previous authors [25,27,29].

Additional considerations to reach the targets of a successful decarbonization pathway include oil and gas reserves, biomass potential, hydrogen infrastructure, and CO2 management:

- The development of exploratory activities in the petroleum industry although counterintuitive, is necessary for achieving the levels of fossil fuel reserves considered in the study as described in section 2.1.4 The crude oil is relevant for the transport sector and natural gas is essential for industry, residential and commercial sectors, in order to guarantee domestics resources and a respective safe energy transition in the next two decades protected from external volatilities.
- Biomass potential was quite conservative in the assumptions and have space to broaden the energy supply in the power, transport, and industry sectors if adequate policies are implemented.
- The use of hydrogen presents multiple challenges in the whole value chain due to its chemical features and will require significant financial and technical efforts to develop the infrastructure that is expected to deliver around 2400 kt of hydrogen per year by 2050.
- Finally, the model uses all the CO_2 storage capacity defined by the study (i.e., 360 MtCO_2e), thus additional options of geological storage or possible uses of CO_2, for instance, synthetic fuel production, should be considered to provide wider possibilities for CCS technologies.

The decarbonization pathways set a tremendous need of technological deployment which should start as quick as possible to distribute the efforts uniformly in the next decades. In the same direction as previous authors [16,25–27], the key technologies in the decarbonization process are renewable power, electric and fuel cell vehicles, hydrogen-fueled equipment, and CCS. The unfolding requires enablers which can ease the process taking full advantage of the national capabilities, hereby, policy design should coordinate accordingly. The principal enablers are:

- The international and national private and public sources of investment and financing that mobilize funds to deploy the required installed capacities.
- The promotion of the green national industry to produce the technologies locally, reducing costs and generating new jobs.
- The cooperation industry-academia to research and develop in the optimization of current technologies and the creation of new ones.
- The change in consumer behavior to adopt low-emissions technologies and outpace fossil fuel uses.
- The creation of local human capabilities in the new businesses of the energy transition, through a national program for training in decarbonization for coal and petroleum workers, and the transformation of the petroleum engineering faculties in Colombia towards energy integrated engineering programs.

The link between technologies and enablers is the design and implementation of integrated energy policies described by Figure 15. The policies should promote a systematic and solid movement of human and financial capital considering the welfare of communities, the respect for natural resources, and the contribution to regional economic growth.

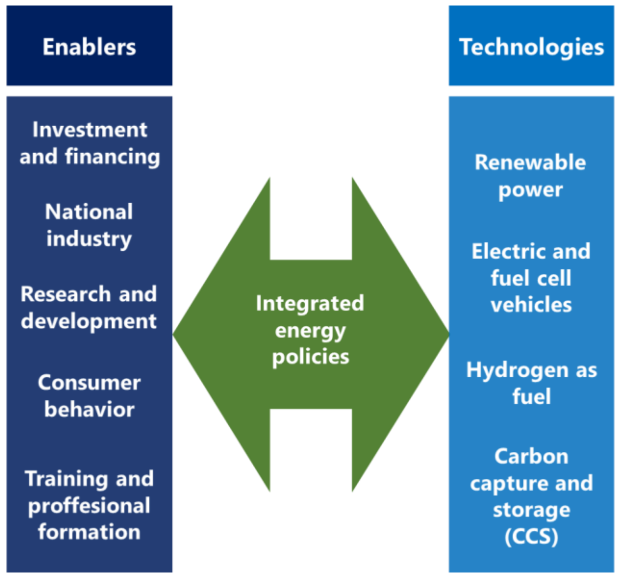

Figure 15. Enablers and key technologies for the decarbonization pathways

4.2. Limitations and opportunities of further research

The modelling approach presents several limitations to be acknowledged and corresponding future research opportunities. First, the temporal and geographical of the model restricts the capability to provide regional and intra-year insights, which could be useful for a high diverse country as Colombia. In terms of the power sector, the location dependency of renewable potentials and the time variability of solar and wind technologies are relevant conditions to be included in additional studies. Secondly, the assumptions were conservative as much as possible, however there is still inherent uncertainty in parameters such as future costs and demands. Implementation of uncertainty quantification techniques such as robust optimization or stochastic programming could evaluate the effects of uncertainty on the results. Thirdly, the impacts of decarbonization on the fiscal system and macroeconomy in a net oil exporter country were not included. Assessing the export balance, the job market and the taxes contribution under the energy transition is important to create integrated measures to avoid fiscal and economic risks. Finally, the model does not include the AFOLU sector, responsible by 56% of GHG emissions. A Climate-Land-Energy-Water system approach (CLEWs) would be valuable in considering the different interlinkages such as biomass to energy, hydro-based technologies, and water for crop irrigation, and formulating robust net-zero policies.

5. Conclusions

The study has presented the modelling process of national energy system decarbonization pathways in Colombia using an open-source optimization methodology. It represents Colombia's first effort to provide a full open tool for integrated energy planning. We built three scenarios over 2021-2050, representing the business-as-usual state, a decarbonization pathway with all technologies available, and an alternative decarbonization pathway without CCS. The OSeMOSYS-COL model was implemented to assess these scenarios and analyze the outcomes in terms of emissions trajectory, energy mix, technology deployment, costs, and benefits. The detailed description of the modelling framework, input data, and assumptions provides a solid baseline for further research in Colombia and support for similar studies in other developing countries.

Our results demonstrate that a Colombian decarbonized energy system brings several advantages compared to a BAU scenario. First, more efficient processes reduce the energy demand by 44%, enhancing the country's energy intensity. Secondly, the mitigation of GHG emissions decreases the carbon intensity by 93% and enables the accomplishment of the Paris agreement commitments. In third place, the replacement of fossil fuels by domestically generated electricity or low-emission hydrogen strengthens the national energy sovereignty and reduces the imports by 90%. Finally, the savings in operational costs, carbon taxes and externalities yield socioeconomic benefits up to 21% of the Colombia's 2021 GDP. In summary, the outcomes show the technical feasibility and socioeconomic benefits of decarbonization goals in Colombia.

Huge transformations through all energy sectors must happen to materialize these results and reach a low-emissions society, therefore concrete action from the stakeholders is necessary. Full renewable power generation, electrification of end-uses, carbon capture and storage (CCS), hydrogen as fuel, and energy efficiency are the key technologies for the decarbonization pathways. Integrated energy policy should promote enablers such as financing sources, promotion of national green industry, interinstitutional research and development, local training and formation, and changes in consumer behavior. Future research can complement the insights of the present study by improving temporal and geographic resolution of modelling, quantifying uncertainties, evaluating fiscal and macroeconomic impacts of the decarbonization, and assessing the CLEWs interlinkages in the energy transition.

Data availability

The data and model code used for this study is fully accessible and licensed under MIT license. Supplementary material is available at Zenodo repository [54].

Credit author statement

Fernando Plazas: Conceptualization, Data curation, Methodology, Formal analysis, Validation, Writing- Original Draft. Rudolf Yeganyan: Project administration, Writing- Review & Editing. Carla Cannone: Writing- Review & Editing. Mark Howells: Supervision. Jairo Quirós-Tortós: Supervision, Writing- Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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U4RIA compliance statement

This work follows the U4RIA guidelines which provide a set of high-level goals relating to conducting energy system analyses in countries [10]. This paper was carried out involving stakeholders in the development of models, assumptions, scenarios and results (Ubuntu / Community). The authors ensure that all data, source code and results can be easily found, accessed, downloaded, and viewed (retrievability), licensed for reuse (reusability), and that the modelling process can be repeated in an automatic way (repeatability). The authors provide complete metadata for reconstructing the modelling process (reconstructability), ensuring the transfer of data, assumptions and results to other projects, analyses, and models (interoperability), and facilitating peer-review through transparency (auditability).

References

[1] IDEAM, Fundación Natura, PNUD, MADS, DNP, CANCILLERÍA, FMAM, TERCER INFORME BIENAL DE ACTUALIZACIÓN DE CAMBIO CLIMÁTICO DE COLOMBIA, Bogotá, D.C., 2021. www.cambioclimatico.gov.co;

[2] Portafolio, Colombia, entre los 11 países con más riesgos “graves” por el clima, (2021). https://www.portafolio.co/economia/finanzas/colombia-es-uno-de-los-paises-con-mas-riesgos-graves-por-el-clima-segun-estados-unidos-557637 (accessed October 31, 2022).

[3] United Nations Framework Convention on Climate Change, Paris Agreement, 2015. https://unfccc.int/sites/default/files/english_paris_agreement.pdf.

[4] Gobierno de Colombia, ACTUALIZACIÓN NDC COLOMBIA-2020 Actualización de la Contribución Determinada a Nivel Nacional de Colombia (NDC), 2020. https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Colombia First/NDC actualizada de Colombia.pdf.

[5] J. DeCarolis, H. Daly, P. Dodds, I. Keppo, F. Li, W. McDowall, S. Pye, N. Strachan, E. Trutnevyte, W. Usher, M. Winning, S. Yeh, M. Zeyringer, Formalizing best practice for energy system optimization modelling, Appl Energy. 194 (2017) 184–198. https://doi.org/10.1016/j.apenergy.2017.03.001.

[6] M. Kueppers, S.N. Paredes Pineda, M. Metzger, M. Huber, S. Paulus, H.J. Heger, S. Niessen, Decarbonization pathways of worldwide energy systems – Definition and modeling of archetypes, Appl Energy. 285 (2021). https://doi.org/10.1016/j.apenergy.2021.116438.

[7] M.G. Prina, G. Manzolini, D. Moser, B. Nastasi, W. Sparber, Classification and challenges of bottom-up energy system models - A review, Renewable and Sustainable Energy Reviews. 129 (2020) 109917. https://doi.org/10.1016/j.rser.2020.109917.

[8] E. Kato, A. Kurosawa, Role of negative emissions technologies (NETs) and innovative technologies in transition of Japan's energy systems toward net-zero CO2 emissions, Sustain Sci. 16 (2021) 463–475. https://doi.org/10.1007/s11625-021-00908-z.

[9] G. Godínez-Zamora, L. Victor-Gallardo, J. Angulo-Paniagua, E. Ramos, M. Howells, W. Usher, F. De León, A. Meza, J. Quirós-Tortós, Decarbonising the transport and energy sectors: Technical feasibility and socioeconomic impacts in Costa Rica, Energy Strategy Reviews. 32 (2020). https://doi.org/10.1016/j.esr.2020.100573.

[10] M. Howells, J. Quiros-Tortos, R. Morrison, H. Rogner, W. Blyth, G. Godínez, L.F. Victor, J. Angulo, F. Bock, E. Ramos, F. Gardumi, L. Hülk, R.L. Institut, E. Peteves, Energy system analytics and good governance-U4RIA goals of Energy Modelling for Policy Support, (2021). https://doi.org/10.21203/rs.3.rs-311311/v1.

[11] R. Morrison, Energy system modeling: Public transparency, scientific reproducibility, and open development, Energy Strategy Reviews. 20 (2018) 49–63. https://doi.org/10.1016/j.esr.2017.12.010.

[12] P. Lopion, P. Markewitz, M. Robinius, D. Stolten, A review of current challenges and trends in energy systems modeling, Renewable and Sustainable Energy Reviews. 96 (2018) 156–166. https://doi.org/10.1016/j.rser.2018.07.045.

[13] S. Oberle, R. Elsland, Are open access models able to assess today's energy scenarios?, Energy Strategy Reviews. 26 (2019) 100396. https://doi.org/10.1016/j.esr.2019.100396.

[14] M. Jaramillo, J. Quirós-Tortós, A. Vogt-Schilb, A. Money, M. Howells, Data-to-Deal (D2D): Open Data and Modelling of Long Term Strategies to Financial Resource Mobilization - the case of Costa Rica, 2023. https://www.cambridge.org/engage/coe/article-details/6417700ddab08ad68f609477 (accessed March 22, 2023).

[15] Universidad Nacional de Colombia & Unidad de Planeación Minero-Energética, Observatorio Colombiano de Energía Aproximación a las condiciones para su conformación, 2018.

[16] UPME, Plan Energético Nacional 2020-2050, 2020. https://www1.upme.gov.co/DemandaEnergetica/PEN_2020_2050/Plan_Energetico_Nacional_2020_2050.pdf.

[17] UPME, Balance Energético Colombiano 2021, 2022. https://www1.upme.gov.co/DemandayEficiencia/Paginas/BECO.aspx (accessed November 2, 2022).

[18] XM, XM PARATEC, (2022). http://paratec.xm.com.co/paratec/SitePages/generacion.aspx?q=capacidad (accessed February 26, 2022).

[19] UPME, Autogeneracion y Generacion Distribuida 2021 , (2021). https://public.tableau.com/app/profile/upme/viz/AutogeneracionyGeneracionDistribuida2021/Historia1 (accessed February 26, 2022).

[20] A. Cadena, A. Haurie, Modelling the Implications of the Kyoto Protocol for a Developing Country, OPSEARCH. 38 (2001) 44–66. https://doi.org/https://doi.org/10.1007/BF03398629.

[21] S. Arango-Aramburo, J. Veysey, J.E. Martínez-Jaramillo, L. Díez-Echavarría, S.L. Calderón, A.M. Loboguerrero, Assessing the impacts of nationally appropriate mitigation actions through energy system simulation: a Colombian case, Energy Effic. 13 (2020) 17–32. https://doi.org/10.1007/s12053-019-09826-7.

[22] Vito, Universidad de los Andes, Propuesta de actualización y consolidación de escenarios de emisiones de GEI por sector y evaluación de costos de abatimiento asociados en Colombia, 2020. https://www.minambiente.gov.co/wp-content/uploads/2021/10/cambio-climatico-Informe-sobre-el-desarrollo-y-los-supuestos-para-la-realizacion-de-escenarios-de-referencia-ndc.pdf.

[23] O. Pupo-Roncallo, J. Campillo, D. Ingham, K. Hughes, M. Pourkashanian, Large scale integration of renewable energy sources (RES) in the future Colombian energy system, Energy. 186 (2019) 115805. https://doi.org/10.1016/j.energy.2019.07.135.

[24] J. Benavides, S. Cabrales, M.E. Delgado, Transición energética en Colombia: Política, costos de la carbono-neutralidad acelerada y papel del gas natural, 2022. https://www.repository.fedesarrollo.org.co/bitstream/handle/11445/4318/Repor_Agosto_2022_Benavides_Cabrales_y_Delgado.pdf?sequence=3&isAllowed=y (accessed December 7, 2022).

[25] R. Delgado, T.B. Wild, R. Arguello, L. Clarke, G. Romero, Options for Colombia's mid-century deep decarbonization strategy, Energy Strategy Reviews. 32 (2020). https://doi.org/10.1016/j.esr.2020.100525.

[26] R. Arguello, R. Delgado, M. Espinosa, T. Gonzalez, J.M. Sandoval, Análisis costo-beneficio de las opciones para alcanzar cero emisiones netas en Colombia, 2022. https://publications.iadb.org/es/analisis-costo-beneficio-de-las-opciones-para-alcanzar-cero-emisiones-netas-en-colombia (accessed November 1, 2022).

[27] S. Calderón, A.C. Alvarez, A.M. Loboguerrero, S. Arango, K. Calvin, T. Kober, K. Daenzer, K. Fisher-Vanden, Achieving CO2 reductions in Colombia: Effects of carbon taxes and abatement targets, Energy Econ. 56 (2014) 575–586. https://doi.org/10.1016/j.eneco.2015.05.010.

[28] M.A. Gonzalez-Salazar, M. Venturini, W.R. Poganietz, M. Finkenrath, T. Kirsten, H. Acevedo, P.R. Spina, A general modeling framework to evaluate energy, economy, land-use and GHG emissions nexus for bioenergy exploitation, Appl Energy. 178 (2016) 223–249. https://doi.org/10.1016/j.apenergy.2016.06.039.

[29] A. Younis, R. Benders, R. Delgado, T. Lap, M. Gonzalez-Salazar, A. Cadena, A. Faaij, System analysis of the bio-based economy in Colombia: A bottom-up energy system model and scenario analysis, Biofuels, Bioproducts and Biorefining. (2020) 1–21. https://doi.org/10.1002/bbb.2167.

[30] M. Cobo, C. Barraza, N. Cantillo, M. Uribe, Recomendaciones para el desarrollo de la economía del hidrógeno en Colombia, 2022. https://www.mec-h2.com/ (accessed November 1, 2022).

[31] Ministerio de Minas y Energía, Banco Interamericano de Desarrollo, UK Government, Hoja del Ruta del Hidrogeno en Colombia, 2021.

[32] F.A. Plazas-Niño, N.R. Ortiz-Pimiento, E.G. Montes-Páez, National energy system optimization modelling for decarbonization pathways analysis: A systematic literature review, Renewable and Sustainable Energy Reviews. 162 (2022) 112406. https://doi.org/10.1016/j.rser.2022.112406.

[33] M. Howells, H. Rogner, N. Strachan, C. Heaps, H. Huntington, S. Kypreos, A. Hughes, S. Silveira, J. Decarolis, M. Bazillian, A. Roehrl, OSeMOSYS : The Open Source Energy Modeling System An introduction to its ethos , structure and development, Energy Policy. 39 (2011) 5850–5870. https://doi.org/10.1016/j.enpol.2011.06.033.

[34] F. Gardumi, A. Shivakumar, R. Morrison, C. Taliotis, O. Broad, A. Beltramo, V. Sridharan, M. Howells, J. Hörsch, T. Niet, Y. Almulla, E. Ramos, T. Burandt, G.P. Balderrama, G.N. Pinto de Moura, E. Zepeda, T. Alfstad, From the development of an open-source energy modelling tool to its application and the creation of communities of practice: The example of OSeMOSYS, Energy Strategy Reviews. 20 (2018) 209–228. https://doi.org/10.1016/j.esr.2018.03.005.

[35] M. Groissböck, Are open source energy system optimization tools mature enough for serious use?, Renewable and Sustainable Energy Reviews. 102 (2019) 234–248. https://doi.org/10.1016/j.rser.2018.11.020.

[36] T.B. da Silva, P. Baptista, C.A. Santos Silva, L. Santos, Climate change mitigation policies in the transportation sector in Rio de Janeiro, Brazil, Environments - MDPI. 7 (2020) 1–22. https://doi.org/10.3390/environments7110099.

[37] D. Groppi, S. Kumar Pinayur Kannan, F. Gardumi, D. Astiaso Garcia, Optimal planning of energy and water systems of a small island with a hourly OSeMOSYS model, Energy Convers Manag. 276 (2023). https://doi.org/10.1016/j.enconman.2022.116541.

[38] A. Vargiu, R. Novo, C. Moscoloni, E. Giglio, G. Giorgi, G. Mattiazzo, An Energy Cost Assessment of Future Energy Scenarios: A Case Study on San Pietro Island, Energies (Basel). 15 (2022). https://doi.org/10.3390/en15134535.

[39] M. V. Rocco, E. Fumagalli, C. Vigone, A. Miserocchi, E. Colombo, Enhancing energy models with geo-spatial data for the analysis of future electrification pathways: The case of Tanzania, Energy Strategy Reviews. 34 (2021). https://doi.org/10.1016/j.esr.2020.100614.

[40] M. Howells, B. Boehlert, P.C. Benitez, Potential climate change risks to meeting Zimbabwe's NDC goals and how to become resilient, Energies (Basel). 14 (2021). https://doi.org/10.3390/en14185827.

[41] D.S. Timmons, K. Elahee, M. Lin, Energy efficiency and conservation values in a variable renewable electricity system, Energy Strategy Reviews. 43 (2022). https://doi.org/10.1016/j.esr.2022.100935.

[42] T.W. Mekonnen, S.T. Teferi, F.S. Kebede, G. Anandarajah, Assessment of Impacts of Climate Change on Hydropower-Dominated Power System—The Case of Ethiopia, Applied Sciences (Switzerland). 12 (2022). https://doi.org/10.3390/app12041954.

[43] I. Pappis, C. Centurion, E.P. Ramos, M. Howells, S. Ulloa, E. Ortigoza, P.E. Gardel-Sotomayor, T. Alfstad, Implications to the electricity system of Paraguay of different demand scenarios and export prices to Brazil, Energy Systems. 12 (2021) 911–939. https://doi.org/10.1007/s12667-020-00420-w.

[44] R.D.H. Fonseca, F. Gardumi, Assessing the Impact of Applying Individual Discount Rates in Power System Expansion of Ecuador Using OSeMOSYS, International Journal of Sustainable Energy Planning and Management. 33 (2022) 35–52. https://doi.org/10.5278/ijsepm.6820.

[45] F. Gardumi, N. Mhiri, M. Howells, F. Bock, T. Necibi, C. Bouden, A scenario analysis of potential long-term impacts of COVID-19 on the Tunisian electricity sector, Energy Strategy Reviews. 38 (2021). https://doi.org/10.1016/j.esr.2021.100759.

[46] A. Dhakouani, F. Gardumi, E. Znouda, C. Bouden, M. Howells, Long-term optimisation model of the Tunisian power system, Energy. 141 (2017) 550–562. https://doi.org/10.1016/j.energy.2017.09.093.

[47] S. Bahetta, R. Hasnaoui, Analyses of Optimum Production Scenarios for Sustainable Power Production in Morocco, Review of Economics and Finance. 19 (2021) 184–195.

[48] J.M. Olsson, F. Gardumi, Modelling least cost electricity system scenarios for Bangladesh using OSeMOSYS, Energy Strategy Reviews. 38 (2021). https://doi.org/10.1016/j.esr.2021.100705.

[49] Y.Y. Rady, M. V. Rocco, M.A. Serag-Eldin, E. Colombo, Modelling for power generation sector in Developing Countries: Case of Egypt, Energy. 165 (2018) 198–209. https://doi.org/10.1016/j.energy.2018.09.089.

[50] H.T.J. Henke, F. Gardumi, M. Howells, The open source electricity Model Base for Europe - An engagement framework for open and transparent European energy modelling, Energy. 239 (2022). https://doi.org/10.1016/j.energy.2021.121973.

[51] S. Motalebi, T. Barnes, L. Lu, B.D. Leibowicz, T. Niet, The role of U.S.-Canada electricity trade in North American decarbonization pathways, Energy Strategy Reviews. 41 (2022). https://doi.org/10.1016/j.esr.2022.100827.

[52] T. Santos, Regional energy security goes South: Examining energy integration in South America, Energy Res Soc Sci. 76 (2021). https://doi.org/10.1016/j.erss.2021.102050.

[53] KTH, OSeMOSYS Documentation, (2018). https://osemosys.readthedocs.io/en/latest/index.html# (accessed March 23, 2023).

[54] F.A. Plazas-Niño, Repository Supplementary Material | Research Article: Informing Sustainable Energy Policy in Developing Countries: An Assessment of Decarbonization Pathways in Colombia Using Open Energy System Optimization Modelling, 2023. https://doi.org/10.5281/zenodo.7995647.

[55] W. Usher, OSeMOSYS GitHub repository, GitHub. (2016). https://github.com/OSeMOSYS/OSeMOSYS (accessed June 5, 2023).

[56] Celsia, Documento de trabajo sobre el Sistema Interconectado Nacional, SIN, (2021). https://www.celsia.com/wp-content/uploads/2021/02/Documento-de-trabajo-sobre-el-Sistema-Interconectado-Nacional.pdf (accessed November 7, 2022).

[57] DNP, CONPES 3918 ESTRATEGIA PARA LA IMPLEMENTACIÓN DE LOS OBJETIVOS DE DESARROLLO SOSTENIBLE (ODS) EN COLOMBIA, 2018.

[58] F.A. Plazas-Niño, N.R. Ortiz-Pimiento, J. Quirós-Tortós, Supporting energy system modelling in developing countries: Techno-economic energy dataset for open modelling of decarbonization pathways in Colombia, Data Brief. 48 (2023) 109268. https://doi.org/https://doi.org/10.1016/j.dib.2023.109268.

[59] UPME, Balance de energía útil, (2022). https://www1.upme.gov.co/DemandayEficiencia/Paginas/Modelos-analiticos.aspx (accessed November 25, 2022).

[60] Corficolombiana, Actualización Proyecciones Económicas: Cambio de Rumbo en Tiempos de Incertidumbre, 2022. https://investigaciones.corficolombiana.com/documents/38211/0/Informe%20Especial%20-

%20Proyecciones%20econ%C3%B3micas%202022-%202024%20v3.pdf/d85ead28-413b-4bac-cc17-ac6c2c08a669 (accessed November 2, 2022).

[61] Banco de la República, Producto Interno Bruto (PIB), (2022). https://www.banrep.gov.co/es/estadisticas/producto-interno-bruto-pib (accessed November 2, 2022).

[62] UPME, BEU Sector Residencial y Terciario, 2019. https://www1.upme.gov.co/DemandayEficiencia/Documents/Balance_energia_util/BEU-Residencial.pdf (accessed December 7, 2022).

[63] EPERLab-UCR, OSeMOSYS-CR Documentation, (2020). https://osemosys-cr.readthedocs.io/en/latest/index.html (accessed December 19, 2022).

[64] Y. Zhang, D. Davis, M.J. Brear, The role of hydrogen in decarbonizing a coupled energy system, J Clean Prod. 346 (2022). https://doi.org/10.1016/j.jclepro.2022.131082.

[65] E. Yáñez, A. Ramírez, V. Núñez-López, E. Castillo, A. Faaij, Exploring the potential of carbon capture and storage-enhanced oil recovery as a mitigation strategy in the Colombian oil industry, International Journal of Greenhouse Gas Control. 94 (2020). https://doi.org/10.1016/j.ijggc.2019.102938.

[66] IPSE - CNM, Caracterización Energética de las ZNI , (2022). https://ipse.gov.co/cnm/caracterizacion-de-las-zni/ (accessed May 25, 2022).

[67] UPME, Planes de abastecimiento, (2021). https://www1.upme.gov.co/Paginas/Hidrocarburos.aspx (accessed May 29, 2022).

[68] UPME, BEU Sector Transporte, 2019. https://www1.upme.gov.co/DemandayEficiencia/Documents/Balance_energia_util/BEU-Transporte.pdf (accessed December 7, 2022).

[69] UPME, BEU Sector Industrial, 2019. https://www1.upme.gov.co/DemandayEficiencia/Documents/Balance_energia_util/BEU-Industria.pdf (accessed December 7, 2022).

[70] Energía Estratégica, El listado de los adjudicatarios de la subasta de renovables en Colombia: Trina Solar, AES, Celsia y EDPR fueron los ganadores - Energía Estratégica, (2019). https://www.energiaestrategica.com/el-listado-de-los-adjudicatarios-de-la-subasta-de-renovables-en-colombia-trina-solar-aes-celsia-y-edpr-fueron-los-ganadores/ (accessed March 26, 2022).

[71] La República, Ganadores de subasta de las energías renovables adquirieron obligación de 796,3 MW, (2021). https://www.larepublica.co/economia/ganadores-de-subasta-de-energia-renovables-adquirieron-obligacion-de-800-mw-3253267 (accessed March 26, 2022).

[72] UPME, INFORME DE AVANCE PROYECTOS DE GENERACIÓN – JULIO 2022, 2022. https://www1.upme.gov.co/siel/Seguimiento_proyectos_generacion/Informe_Avance_proyectos_Generacion_Julio2022.pdf (accessed December 25, 2022).

[73] XM, Synergox Oferta y Generación, (2022). https://sinergox.xm.com.co/oferta/Paginas/Historicos/Historicos.aspx?RootFolder=%2Foferta%2FHistricos%2FGeneraci%C3%B3n&FolderCTID=0x012000B3FC86CB37661147B52CAE93637C1249&View=%7B946210C0%2D4071%2D4173%2D964C%2DED5BCCE4E66C%7D#InplviewHash946210c0-4071-4173-964c-ed5bcce4e66c= (accessed November 6, 2022).

[74] UPME, EVALUACIÓN DE LAS CONDICIONES DEL ENTORNO NACIONAL E INTERNACIONAL DEL SECTOR DE HIDROCARBUROS Y ANÁLISIS DE LAS VARIABLES CRÍTICAS QUE IMPACTAN SU DESARROLLO, 2021.

[75] UPME, ESTUDIO TÉCNICO PARA EL PLAN DE ABASTECIMIENTO DE GAS NATURAL, 2020. https://www1.upme.gov.co/Hidrocarburos/publicaciones/PAGN_2019-2028.pdf (accessed December 7, 2022).

[76] Ministerio de Minas y Energía, Minería de Carbón en Colombia. Transformando el futuro de la industria, 2021. https://www.minenergia.gov.co/documents/10192/24311177/documento+carbon%284%29.pdf.

[77] Portafolio, Colombia explora sus reservas de uranio, (2017). https://www.portafolio.co/negocios/colombia-explora-sus-reservas-de-uranio-503210 (accessed May 28, 2022).

[78] S.G. Orrego, Análisis espacial multicriterio para la ubicación de parques eólicos y granjas solares en Colombia, Medellín, Colombia, 2021.

[79] Renewables Consulting Group, Hoja de ruta para el despliegue de la energía eólica costa afuera en Colombia, 2022. https://www.minenergia.gov.co/static/ruta-eolica-offshore/src/document/Espa%C3%B1ol%20Hoja%20de%20ruta%20energ%C3%ADa%20e%C3%B3lica%20costa%20afuera%20en%20Colombia%20VE.pdf (accessed March 22, 2022).

[80] C. Alfaro, J.B. Rueda-Gutiérrez, Y. Casallas, G. Rodríguez, J. Malo, Approach to the geothermal potential of Colombia, Geothermics. 96 (2021). https://doi.org/10.1016/j.geothermics.2021.102169.

[81] SIMCO, Informacion estadística minera, (2022). https://www1.upme.gov.co/simco/Cifras-Sectoriales/paginas/informacion-estadistica-minera.aspx (accessed May 25, 2022).

[82] ANH, Datos y estadísticas - Agencia Nacional de Hidrocarburos, (2021). https://www.anh.gov.co/es/operaciones-y-regal%C3%ADas/datos-y-estadisticas/ (accessed May 3, 2022).

[83] UPME, PROYECCIÓN DE PRECIOS DE LOS ENERGÉTICOS EN FUENTE DE PRODUCCIÓN Y EN PLANTAS DE GENERACIÓN, 2021. https://www1.upme.gov.co/Paginas/Hidrocarburos.aspx (accessed November 27, 2022).

[84] Valora Analitik, Reforma tributaria Colombia: ¿cómo quedó el impuesto al carbono?, (2022). https://www.valoraanalitik.com/2022/11/01/reforma-tributaria-colombia-asi-quedo-impuesto-carbono/ (accessed March 24, 2023).

[85] D. Coady, I. Parry, N.-P. Le, B. Shang, Global Fossil Fuel Subsidies Remain Large: An Update Based on Country-Level Estimates, 2019. https://www.imf.org/en/Publications/WP/Issues/2019/05/02/Global-Fossil-Fuel-Subsidies-Remain-Large-An-Update-Based-on-Country-Level-Estimates-46509 (accessed December 10, 2022).

[86] UNEP, IS NATURAL GAS A GOOD INVESTMENT FOR LATIN AMERICA AND THE CARIBBEAN?, 2022. https://www.unep.org/resources/report/natural-gas-good-investment-latin-america-and-caribbean#:~:text=Is%20Natural%20Gas%20a%20Good%20Investment%20for%20Latin%20America%20and%20the%20Caribbean%3F,-24%20October%202022&text=This%20report%20reveals%20that%20an,by%20far%20the%20best%20choice. (accessed March 24, 2023).

[87] S. Pfenninger, A. Hawkes, J. Keirstead, Energy systems modeling for twenty-first century energy challenges, Renewable and Sustainable Energy Reviews. 33 (2014) 74–86. https://doi.org/10.1016/j.rser.2014.02.003.

[88] G. Limpens, H. Jeanmart, F. Maréchal, Belgian energy transition: What are the options?, Energies (Basel). 13 (2020) 1–29. https://doi.org/10.3390/en13010261.

[89] OLADE, Panorama Energético de América Latina y el Caribe 2022, 2022.

[90] Gobierno de Colombia, Estrategia climática de largo plazo de Colombia E2050 para cumplir con el Acuerdo de París, Bogotá, 2021. https://e2050colombia.com/wp-content/uploads/2022/04/Estrategia-Climatica-de-Largo-Plazo-de-Colombia-E2050.pdf (accessed October 24, 2022).

[91] S. Cloete, C. Arnaiz del Pozo, Á. Jiménez Álvaro, System-friendly process design: Optimizing blue hydrogen production for future energy systems, Energy. 259 (2022). https://doi.org/10.1016/j.energy.2022.124954.

[92] H. Blanco, W. Nijs, J. Ruf, A. Faaij, Potential for hydrogen and Power-to-Liquid in a low-carbon EU energy system using cost optimization, Appl Energy. 232 (2018) 617–639. https://doi.org/10.1016/j.apenergy.2018.09.216.

[93] UPME, Plan Indicativo Programa de Uso Racional y Eficiente de la Energía, 2021. https://www1.upme.gov.co/DemandayEficiencia/Documents/PROURE/Documento_PROURE_2022-2030_v4.pdf (accessed March 24, 2023).

[94] I. Staffell, D. Scamman, A. Velazquez Abad, P. Balcombe, P.E. Dodds, P. Ekins, N. Shah, K.R. Ward, The role of hydrogen and fuel cells in the global energy system, Energy Environ Sci. 12 (2019) 463–491. https://doi.org/10.1039/c8ee01157e.