

Article

The Energy Transition in Colombia: Government Projections and Realistic Scenarios

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Abstract

Energy transition is crucial for climate change mitigation and Sustainable Development Goals (SDGs), and has been a key government focus in Colombia since 2022, which must carefully consider its energy roadmap. This study evaluates three potential scenarios for achieving nearly 100% renewable energy by 2035: replacing fossil fuels with biofuels, using hydrogen for transport and industrial heat, and relying entirely on renewable electricity. This paper discusses these scenarios' technical, economic, and social challenges, including the need for substantial investments in renewable energy technologies and energy storage systems to replace fossil fuels. The discussion highlights the importance of balancing energy security, environmental concerns, and economic growth while addressing social priorities such as poverty eradication and access to healthcare and education. The results show that while the Colombian government's energy transition goals are commendable, a rapid energy transition requires 4 to 8 times the government's projected 34 billion USD investment, making it economically unfeasible. Notably, focusing on wind, photovoltaic, and green hydrogen systems, which need storage, is too costly. Furthermore, replacing fossil fuels in transport is impractical, though increasing biofuel production could partially substitute fossil fuels. Less energy-intensive alternatives like trains and waterway transport should be considered to reduce energy demand and carbon footprint.

Keywords: energy transition; renewable energy; energy mix



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1. Introduction

Energy is essential for economic growth and is paramount for poverty eradication, reducing inequalities, and improving access to healthcare, education, water, etc. [1,2]. However, anthropogenic Greenhouse Gas (GHG) emissions have increased since the Industrial Revolution, primarily because of energy, with the energy sector accounting for 34% of global GHG emissions [3]. The predominance of climate change in the global discussion placed the energy transition at the center of the GHG mitigation strategies.

Reducing and decarbonizing energy demand is paramount to meeting climate change mitigation targets worldwide. The transition raises challenges and potential trade-offs related to energy security, environmental concerns, economic disruption, and social impacts that must be considered before moving forward. Transitioning to carbon neutrality will impose high costs on companies [4] and can be particularly challenging for carbon-intensive

and energy-exporting regions, affecting industrial activities and potentially imposing higher social costs [5,6].

The focus of decarbonizing the energy sector is on electricity generation, transmission, and distribution systems, and in the transition to Electric Vehicles (EVs) [7], with the electric grid infrastructure considered as the primary renewable energy delivery system to consumers [8]. In a sustainable development scenario by 2040, the energy transition will drastically increase the demand for critical minerals (i.e., lithium, cobalt, nickel, copper, rare earth metals) for clean energy technologies, with a global net-zero scenario by 2050 increasing this demand by six-fold [9]. This dependency creates new supply chain vulnerabilities, as shortages in the mineral supply will make them less affordable, delaying the energy transition [9,10].

The transition to renewable energy systems presents a significant global challenge, particularly for developing and energy-exporting nations where the economic implications are substantial. The literature consistently highlights that the high upfront capital investment required for variable renewable energy (VRE) technologies, such as solar and wind, constitutes a primary barrier to their large-scale deployment. Studies show that elevated financing costs can represent up to 50% of the levelized cost of electricity in emerging markets, severely undermining the competitiveness of renewables [11]. Thus, the economic feasibility of the energy transition is inextricably linked to the ability to secure low-cost, long-term capital, a challenge amplified in economies reliant on hydrocarbon revenues [12,13].

Despite a growing body of research on the techno-economic aspects of renewable technologies, a significant gap persists in the literature concerning the direct comparison between official government projections and independently modeled, realistic transition scenarios within specific national contexts. While studies explore technological innovation or the necessity of energy storage solutions [14,15], they often do so without a granular assessment of the capital expenditure (CAPEX) required to achieve ambitious national targets.

The existing literature, therefore, often overlooks a critical question: are the energy transition roadmaps announced by governments in developing countries, such as Colombia, grounded in a feasible economic reality, or do they underestimate the immense investment required? This paper aims to fill this crucial research gap by providing a rigorous techno-economic analysis that directly contrasts Colombia's governmental projections with realistic scenarios, thereby offering a vital reality check on the nation's energy future.

Colombia's government agenda centers on developing a fair and sustainable energy transition, with concrete measures to combat climate change and phase out fossil fuel extraction and use [16–18]. President Gustavo Petro has stressed the importance of a swift process focused on reducing CO₂ emissions, with an estimated investment of 34 billion USD to reach a 100% clean energy mix [19].

Although it's commendable that the Colombian government focuses on the energy transition aligned with international goals, complex interactions and trade-offs between climate change and sustainable development complicate decision-making [20,21]. The energy transition costs must be assessed to identify when they become too expensive, as climate policies can affect economic growth and aggravate inequality [1,21,22].

Consequently, significant concerns exist regarding the feasibility of the government's projected transition and potential risks to energy security and economic welfare. This study, therefore, evaluates the financial costs of achieving a 100% clean energy mix in Colombia under different transition scenarios.

2. Energy Balance and Transition Context in Colombia

2.1. Energy Balance

The energy transition scenario needs to be discussed by depicting the energy balance in Colombia, a net exporter of fossil fuels, as shown in Figure 1.

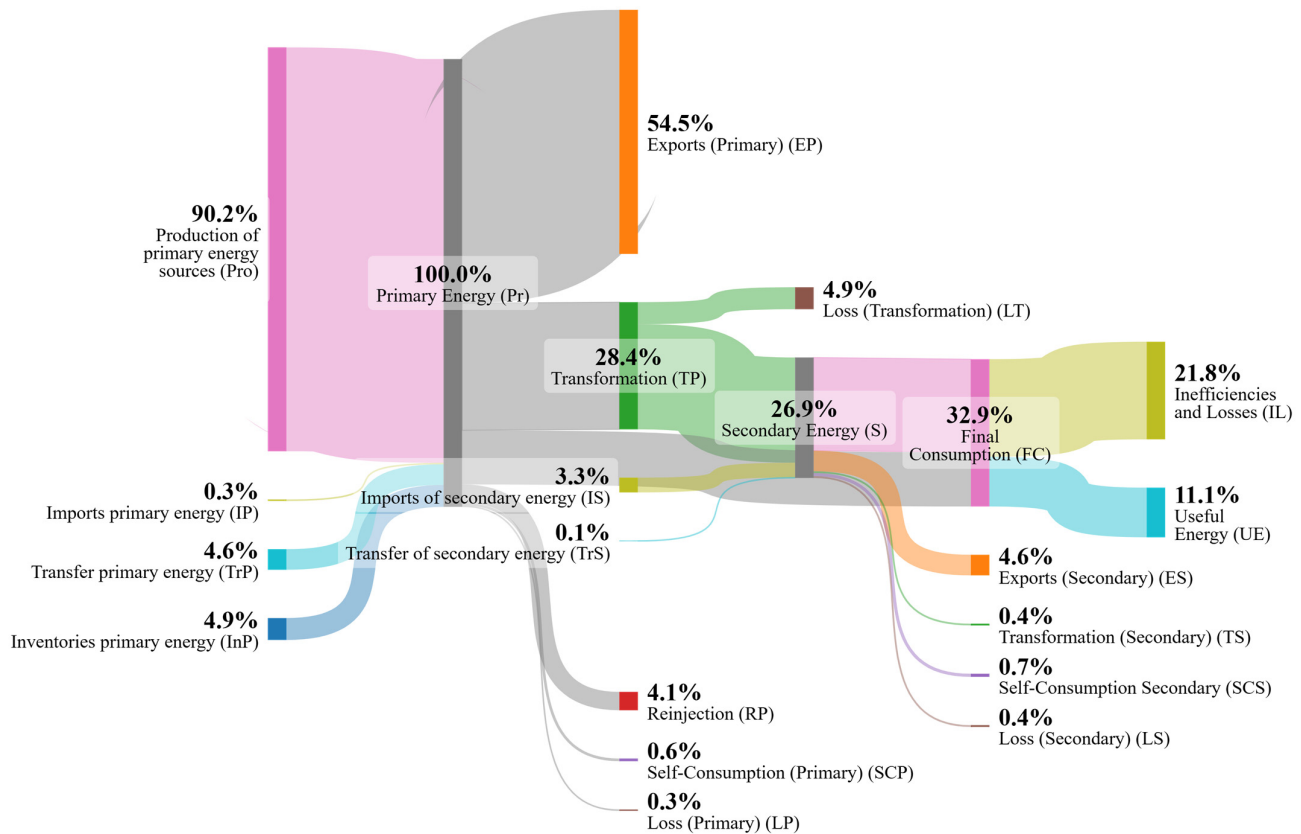


Figure 1. Colombian energy balance 2021 (source: own elaboration with data from [23]).

The production of primary energy sources (Pro) accounts for some 90% of the primary energy mix. The country exports over half of the primary energy annually extracted. About 28% of the primary energy is transformed into secondary energy sources, mainly used within the country. The final consumption mix, which accounts for 33% of the primary energy mix, includes 12% of primary and 21% of secondary energy sources. In total, inefficiencies and energy losses account for 66% of the final energy consumption mix.

The high share of fossil fuels exports (i.e., the oil and gas sector and coal mining) averaged 52% of the national exports since 2005 [24]. The oil and gas sector alone has accounted for 10% to 20% of the Colombian government's income in recent years, driving around 40% of the exports and 20% of foreign investment [25]. Even with the global fuel demand drop because of COVID-19 in 2020, the oil and gas sector accounted for 12% of the government's income [26]. Fossil fuels averaged 4.7% of GDP between 2005 and 2021, accounting for 3.5% in 2021 [27].

Figure 2 displays the final energy consumption mix by energy source and economic sector.

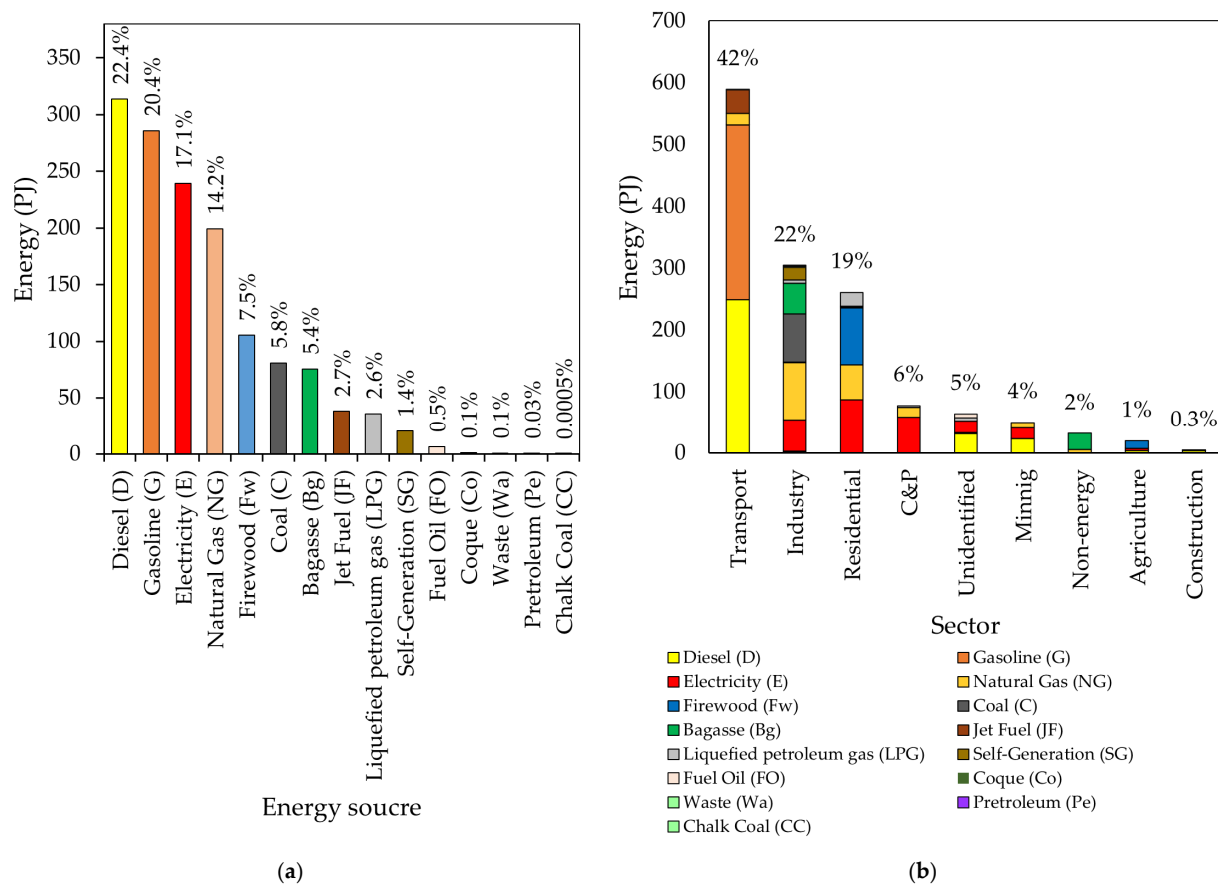


Figure 2. Final energy consumption mix 2021: (a) Energy consumption per source; (b) Energy consumption per sector (source: own elaboration with data from [23]). C&P: Commercial and Public.

Results show that the demand for diesel, gasoline, electricity, and natural gas accounts for 74% of the final energy use. Firewood used mainly for cooking in low-income and rural areas accounts for some 8%. Moreover, the transport sector uses 42% of the final energy mix, including 79.5% of the national diesel consumption and 90% of gasoline. Road transport accounted for 92.4% of the fuel demand, with 66.7% used for road passenger transport and 25.7% used for freight transport. Other means of transport, such as railroad, air, river, and marine transport, account for 7.6% of the sectoral energy used.

Industry used 27.8% of the national electricity (including 100% of self-generation). Additionally, the industry used 97% of carbon and 65.8% of bagasse, partly for heat generation and partly to support electricity self-generation. In total, 68.6% of the fuel was used to support the industrial demand for heat for direct applications (e.g., hot gases from industrial furnaces or electric heating in the industry) or indirect (e.g., steam from boilers) [28]. The industrial sector supports 59% of its energy consumption with solid, liquid, and gaseous fossil fuels, 16% with bagasse, and 24% with grid electricity and from self-generation. Some 23% of the energy used for self-generation is renewable, while the remaining 77% is based on fossil fuels.

Finally, the residential sector uses 33.6% of the electricity while demanding 28.3% of the natural gas and 87.3% of the firewood, mainly for cooking. Firewood is chiefly used for cooking in inefficient 3-stone fires in rural areas, which have significant social and environmental consequences. Other sectors account for lower electricity, diesel, and bagasse consumption. In total, energy for heating accounts for 38% of the energy demand.

If the energy transition in Colombia aims to curb GHG emissions, the final energy consumption mix shows that the focus must be on replacing diesel and gasoline in the

transport sector, particularly for road transport. Furthermore, it must consider alternatives to fossil fuels for industrial heating and the heat demanded in residential, commercial, and public sectors. Moreover, it is advisable to supplement hydraulic-based electricity with alternative renewable energy sources to substitute fossil fuels within the electricity distribution and fulfill the forecasted requirements.

The electric power generation capacity installed in Colombia amounted to 17,673 MW in 2022, producing 73,934 GWh [29]. Electricity generation in the country evolved from a mix primarily based on hydroelectricity to a higher share of fossil fuels, forced by climatic events affecting hydroelectric plants [30].

The national electricity mix is shown in Figure 3.

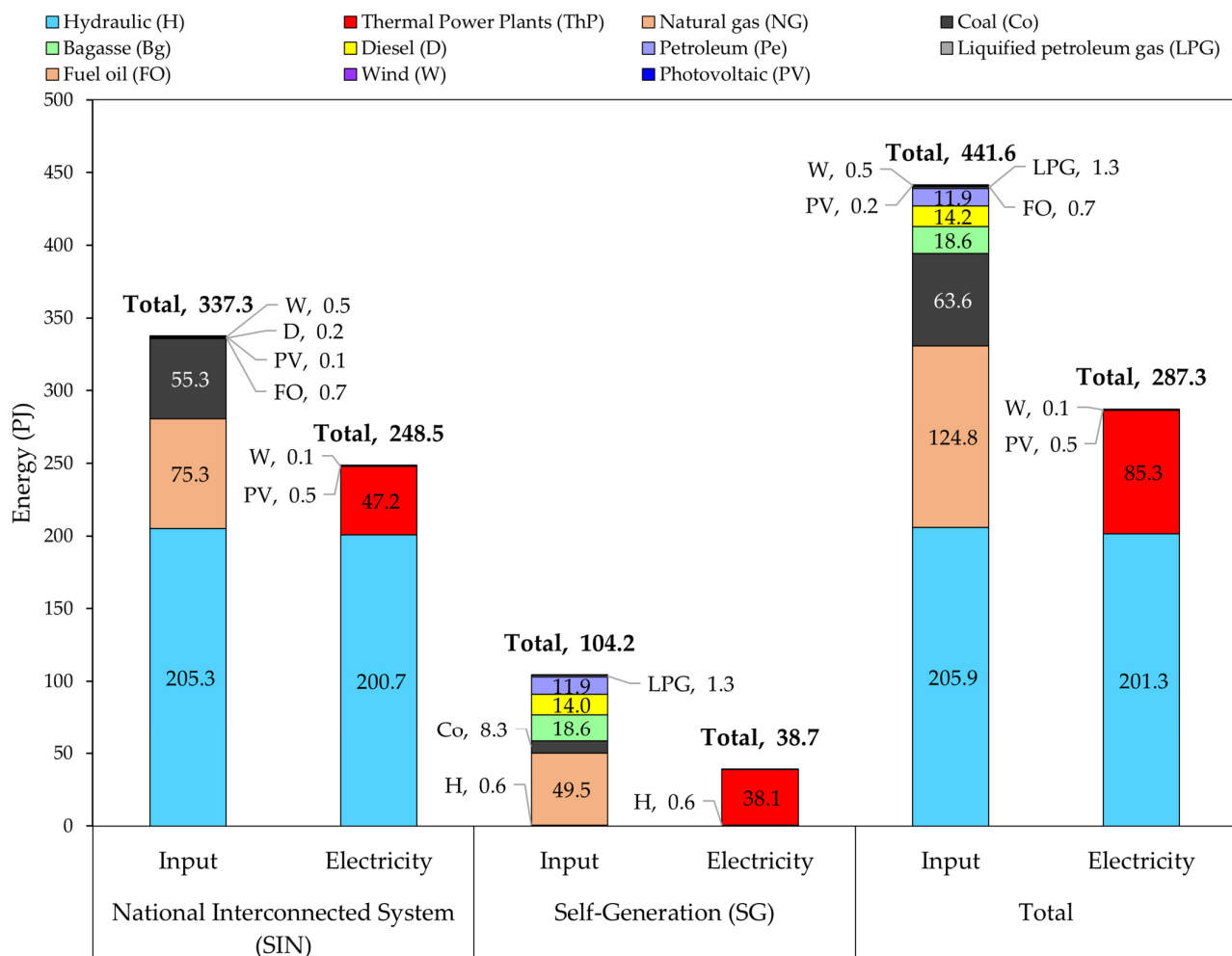


Figure 3. Energy sources for electricity generation (average between 2017 and 2021) (source: own elaboration with data from [29]).

Results show that hydroelectric power plants accounted for 49% of the total mix, underlining a highly renewable electricity mix, with a peak of 218 PJ in 2021. Furthermore, natural gas accounted for 10% to 12%, and coal accounted for 4% to 12%, with a tendency to reduce its share. Other sources, such as non-conventional renewable energy, comprised less than 2% of the mix. The main issue of the large dependency on hydroelectric-based electricity is the impacts of climatic events like ‘El Niño’, causing droughts and affecting the capacity of the hydroelectric plants to maintain a long-term supply of electricity [31,32]. The output shows hydroelectric power plants to be more efficient than thermal power plants.

The energy demand in Colombia is projected to increase (see Figure 4). These projections consider that electric vehicles will account for 24% of the transport vehicles in 2035 and that the metro of Bogota will initiate operations in 2028 [33].

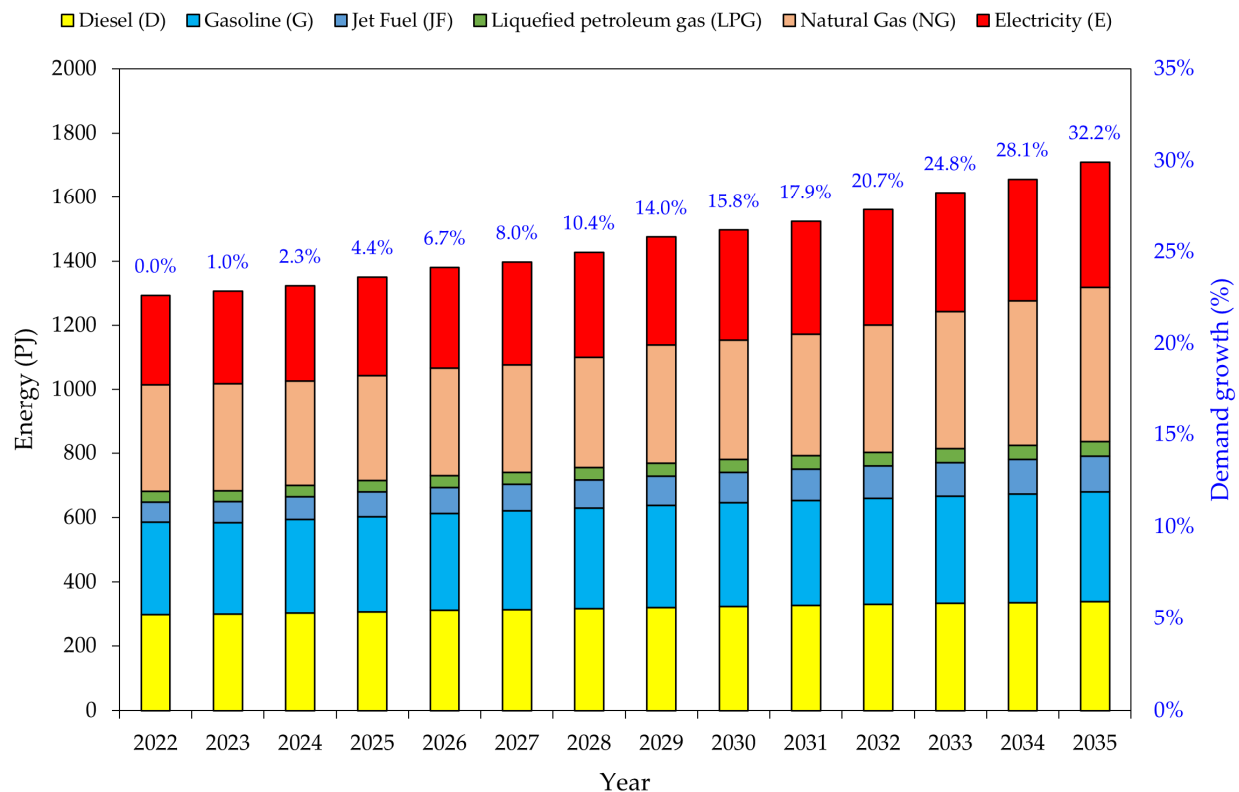


Figure 4. Energy demand projections (source: own elaboration with data from [34]).

Projections foresee that while transport will account for 4.3% of the electricity demand in 2035, the demand for diesel and gasoline for road transport will increase by 14% and 19% in the same period. Moreover, demand for natural gas is projected to increase by 51%. Natural gas demand will be mainly driven by industry (accounting for 40% of the demand), power plants for electricity generation with 38%, and the residential sector with 13%, while transport and the commercial and public sectors account for 9%.

Moreover, electricity demand is projected to increase by 44%, while demand is forecasted to increase by 36% to 15,191 MW. Similarly, the use of liquefied petroleum gas (LPG) is projected to grow by 34%. Energy demand will increase by 32% compared to 2022.

2.2. Current State of Hydrogen Production in Colombia

Colombia's hydrogen economy is in a nascent but critical stage, framed by an ambitious energy transition agenda that designates low-emission hydrogen as a key vector for decarbonization [35,36]. The current production landscape, however, remains overwhelmingly dependent on traditional methods. In 2023, of the approximately 144 kilotons (kt) of hydrogen consumed nationally, the vast majority was grey hydrogen (76%), produced via steam methane reforming (SMR) for captive use in Ecopetrol's refining operations [37,38]. Utilizing SMR with carbon capture, use, and storage (CCUS) technologies, blue hydrogen accounts for an estimated 20% of consumption, with a 2030 production target of 50 kt [36,38].

The low-emission sector is led by green hydrogen (4% of consumption), whose production capacity saw a twelve-fold increase between 2023 and 2024, reaching 416 t/year. This growth is driven by a 36-project pipeline, including flagship initiatives like Ecopetrol's

Project Coral (5 MW) [35,38]. A particularly promising frontier is naturally occurring white hydrogen, which has been legally framed as a renewable source and found in high concentrations in the Llanos basin, positioning Colombia as a potential leader in this low-cost resource [39,40]. This emerging production is supported by a policy framework, notably Law 2099 of 2021, which provides significant tax incentives [36].

Nevertheless, despite strong government support, a formidable gap exists between Colombia's ambitious targets and its current reality. The 2030 goal of 1–3 GW of electrolysis capacity appears challenging, with committed projects only totaling approximately 7 MW and projections for early 2030, anticipating just 511 MW [35]. This discrepancy highlights several critical barriers.

The primary obstacle is economic viability. Green hydrogen's production cost of US\$4–6 per kg far exceeds the 2030 target of 1.7 USD/kg, hindering its competitiveness and resulting in incipient progress in creating new demand [35,38]. Furthermore, the nation faces significant infrastructural and technical deficits. There is a lack of adequate transport and storage facilities, which impedes project scaling [38]. Critically, Colombia lacks a robust national metrology infrastructure capable of certifying hydrogen quality to international standards, a fundamental requirement for safety, efficiency in applications like fuel cells, and access to export markets [41].

Finally, policy implementation has been slow. Key governance bodies like the Monitoring Committee have not been formalized, and Phase 1 of the roadmap (due 2022–2023) was only 51% complete by May 2025 [35]. The aggressive timeline for such a profound industrial transformation is ambitious and risky. A pragmatic approach is needed, recalibrating timelines and prioritizing the mitigation of key bottlenecks (i.e., cost, infrastructure, and metrology) to foster a realistic and sustainable hydrogen economy.

2.3. Energy Transition Objectives

The previous administration of President Iván Duque (2018–2022) approved an energy transition law (Law 2099 of 2021) to increase non-conventional renewable energy sources (i.e., different from large-sized hydroelectric plants), rising from under 1% to approximately 12% of the energy mix by 2022 [42]. However, growth from non-conventional sources has been slower than before projected. The current administration of President Gustavo Petro (2022–present) has outlined more ambitious objectives to promote the energy transition, positioning it at the core of the government's strategic priorities.

This initiative is a central component of the proposed 'Just Energy Transition Roadmap', which highlights a focused commitment to sustainable energy development [16]. The strategic pillars of this roadmap are

- The democratization of energy governance, to broaden public participation in the shift toward renewable sources.
- Fostering energy communities, characterized as diverse organizations including small and medium-sized enterprises, households, and other related entities that actively participate in one or more functions of the energy sector [43].
- The large-scale electrification of the transportation sector.
- Developing the national capacity for green hydrogen production.

The Ministry of Mines and Energy reached multiple agreements to enhance the energy transition effort and promote the development of smart grids, rural electrification solutions, electric mobility, climate change initiatives, hydrogen, and offshore wind projects [44].

Overall, to reduce fossil fuels and GHG emissions, the transport sector, which is currently primarily reliant on gasoline and diesel, needs to transition. Additionally, the energy transition must address the demand for direct and indirect heat in industry, supported mainly by fossil fuels, and the heat demand in the residential, commercial, and public

sectors. In this direction, the share of renewable energies in the electric mix must increase significantly, developing local, regional, and national solutions.

2.4. Study Context

Different technologies are available for the energy transition, from renewable energy carriers like biofuels to end-use technologies like electric vehicles. However, the techno-economic analysis of these pathways in Colombia must be understood nationally. The country's efforts are constrained by a series of well-documented structural, political, and social barriers that shape the implementation landscape [30]:

- Absence of an electric grid in non-interconnected zones.
- High investment and operating costs of renewable energy sources.
- Subsidies for fossil fuels.
- Lack of comprehensive long-term planning and poor public–private coordination.
- Insecurity related to armed conflict in different regions.

Furthermore, while the government's current focus is on wind and Photovoltaic (PV), Colombia possesses other substantial energy resources, including an identified potential for up to 15 GW of biomass-based power generation [30] and 56 GW of hydroelectric systems [45]. The latter, in particular, represents a significant source of stable, low-carbon energy, though its development is often fraught with socio-environmental challenges. These pre-existing conditions and alternative resource potentials provide the essential context for interpreting the feasibility and implications of the scenarios analyzed in this study.

From a policy perspective, it is crucial to note that Colombia contributes only a small fraction to global GHG emissions (0.3 GtCO_{2eq} of the 59 GtCO_{2eq} emitted globally) [46]. Therefore, any transition strategy implies a significant trade-off between investing in decarbonization and addressing urgent national priorities aligned with the SDGs, such as poverty eradication, economic growth, and durable peace. International benchmarks, such as the European Union's 10.8% average share of renewables in transport [47] and the global growth of liquid biofuels [48], also provide important context for assessing the feasibility of national targets.

Finally, a truly “just transition” must address complex issues such as “carbon leakage”—where domestic fossil fuel production is diverted to export markets—and the political economy of the transition, ensuring that benefits are equitably shared and that the social costs of new infrastructure are not disproportionately borne by marginalized communities, as seen in the conflicts in ‘La Guajira’.

This study also considers the potential of other national energy resources, such as the 51 GW identified for medium and large-sized hydroelectric plants [49] and the role of biomass in addressing local and regional energy access [50], as part of a comprehensive assessment.

2.4.1. Renewable Electricity Technologies

Renewable technologies developed to generate renewable electricity from renewable sources include [51]

- Wind;
- Solar;
- Bioenergy;
- Hydropower;
- Geothermal;
- Marine.

Between 2017 and 2022, PV systems accounted for 57% of renewable electricity additions, followed by wind systems at 22%, hydroelectric at 10%, and bioenergy at 3% [52]. Although biomass accounts for the highest renewable potential countrywide [53,54], the Colombian government targets the expansion of wind and PV systems and, to a lower extent small hydroelectric plants [55]. Biomass-based technologies that could provide local and regional solutions are receiving limited promotion [56].

Table 1 shows some general characteristics of wind and PV systems.

Table 1. Wind and PV systems CAPEX (Source: own elaboration with data from [57]).

System	CAPEX (USD/kW)	OPEX (USD/kW)	Lifespan (Years)
Wind Offshore (WOff)	3285–5908	75–116	30
Wind Onshore (WOn)	1462	43	30
PV	1906	19	30

2.4.2. Energy Storage Systems

Whereas fossil-based electric plants operate with controllable output and enough flexibility to balance demand and supply in the electric grid, intermittent renewables like wind turbines and solar PV depend on the availability of wind and sunlight and have no flexibility to balance their output with the grid demand [58]. Therefore, increasing renewable electricity with wind and PV systems is one major technical challenge to balancing the grid. These systems introduce grid stability challenges of voltage swings, power quality, sudden weather-induced changes in generation, and grid protection [59,60].

Large hydroelectric power plants could operate as flexible resources to reduce the need for other energy storage systems [61]. The extensive infrastructure of hydroelectric power plants in Colombia could accommodate the variability of wind and PV systems by reducing their output so the national electric system can meet the demand when PV and wind are unavailable without energy storage. However, it is unlikely that the hydropower plant owners will agree with this approach, which will affect their economic performance.

Moreover, wind and PV systems need more installed power than the controlled output. Thus, wind and PV systems can have more than the 15 GW of installed power projected for 2035, which, at full generation capacity, will supply more than the system's peak demand and will, therefore, require the curtailing of part of the electricity output.

Furthermore, extreme events like 'El Niño', which cause intense drought and water shortages, will prevent hydroelectric plants from accommodating wind and PV systems. Also, if the extreme 'El Niño' event coincides with the low availability of solar and wind sources, energy security will be impacted, affecting the economy and society. Therefore, energy storage systems must operate with high PV and wind-based electricity generation.

Balancing supply and demand in electricity grids with a high share of wind and PV systems requires curtailing the systems' output and energy waste, thus limiting the penetration of these renewable systems [58]. Alternatively, energy storage systems can store excess energy from intermittent renewables to address the time mismatch between generation and demand [62,63], enabling the integration of intermittent renewables into the electric grid [64]. The storage demand increases exponentially with the share of wind and PV in the electricity mix (see Figure 5) [63].

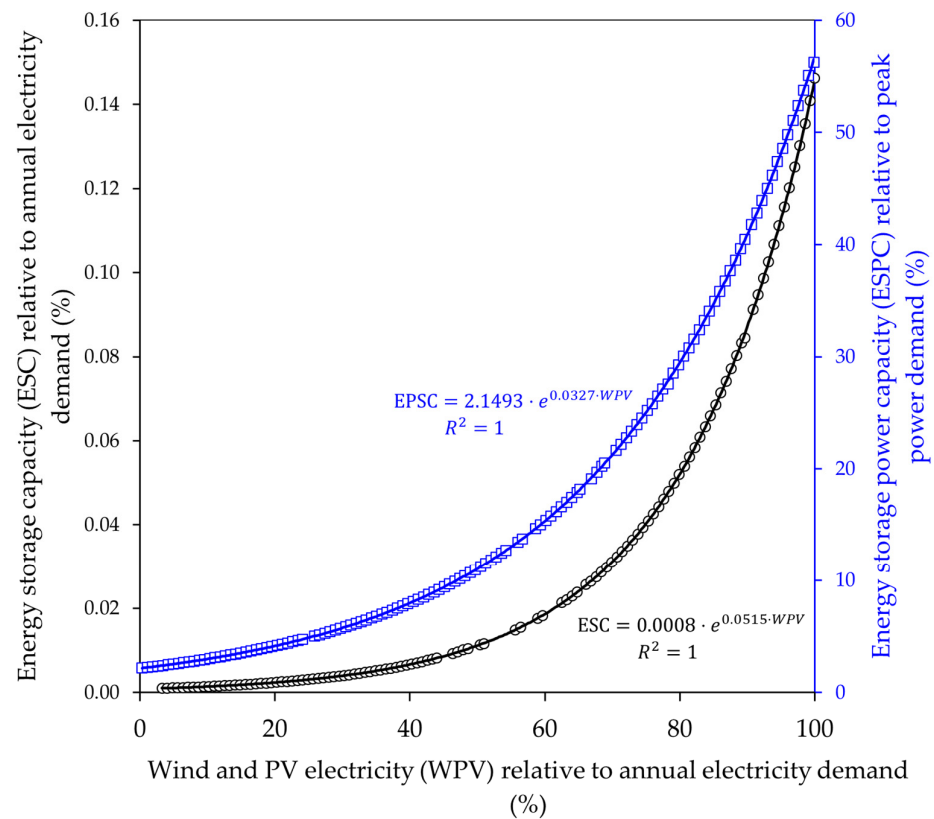


Figure 5. Electricity storage and power capacity requirements as a function of variable renewable energy penetration (source: own elaboration with data from [63]).

To quantify this relationship for our scenario analysis, we derived two empirical equations by fitting exponential curves to the data presented in Figure 5. Equations (1) and (2) are used to estimate the required Energy Storage Capacity (ESC) and Energy Storage Power Capacity (ESPC), respectively, as a direct function of the share of wind and PV electricity (WPV) in the grid:

$$ESC = 0.0008 \cdot e^{0.0515 \cdot WPV} \quad (1)$$

$$ESPC = 2.1493 \cdot e^{0.0327 \cdot WPV} \quad (2)$$

where

ESC—Energy storage;

ESPC—Energy storage power capacity;

WPV—Wind and PV electricity.

Energy storage technologies for bulk and distributed electricity storage are available and under development globally, with different characteristics and Technology Readiness Level (TRL) (see Table 2) [61,65]. The selection of energy storage systems for large-scale applications depends on energy density, efficiency, cost, lifespan, power density, stability, storage capacity, discharge time, and the impact on energy security and the economy [66]. Overall, each technology shows advantages and drawbacks, and no single technology outperforms the others in every aspect, which has trade-offs between characteristics [65].

Table 2. Energy storage systems (source: elaborated with data from [57,61,65–70].

Category	Storage System	Application ^a	CAPEX (USD/kW)	Levelized Cost of Electricity (LCOE) (USD/kWh)	Discharge Time	Energy Density (Wh/kg)	Power Density (W/kg)	Power Range (MW)	Roundtrip Efficiency (%)	Lifetime (Years)	TRL
Electro-chemical batteries	Lead–acid batteries	BDPS	1520–1792	380–448	s–h	30–75	75–300	0–20	79–85	12	9
	Lithium-ion batteries	BDPS	2222	352–487	min–h	100–200	360	0–0.1	86–88	10	9
	Sodium Sulphur	BDPS	2394–5170	599–1293	min–h	150–240	90–230	0.05–8	77–83	15	8
	Liquid Metal	BDPS	-	180–250	s–h	135	-	>1	80–90	20	6–7
	Flow batteries	Nickel-cadmium	1995–2438	499–609	min–h	40–90	150–240	0–40	65–70	15	9
		Vanadium redox			<10 h	35–60	75–150	<3			9
		Polysulfide bromide			<20 h	15–30	-	<15			4–5
		Zinc bromine			s–10 h	75–85	90–110	90–100			6
Mechanical	Compressed air energy storage system	BPS	973–1259	97–126	1–24 h	30–60	3.2–5.5	3–300	52	30	7–8
	Low-speed flywheel	DPS	1080–2880	4320–11,520	s–min	5–80	400–500	0.1–20	86–96	20	9
	Pumped hydro energy storage system	BPS	2640	150–242	1 h–days	0.5–1.5	100–400	10–5000	70–85	60	9
Chemical	H ₂ storage	BPS	2793–3488	279–349	s–24 h	600–1200	5–800	0.1–50	35 ^b	30	5–6
Thermal	Thermal energy storage	BPS	1700–1800	20–60	h	80–250	10–30	250	90	30	7–8
Electrical	Capacitors	DPS	930–74,480	-	ms–1 h	0.05–5	10 ⁵	0–0.05	60–90	10–15	6
	Supercapacitors	DPS	20,000	500–1000	ms–1 h	1.5–2.5	500–5000	0–0.3	75–95	-	8–9
	Superconducting magnetic	DPS	200–300	1000–10,000	ms–8 s	0.5–5	500–2000	1–10	>95	20	5–6

^a BPS—More suitable for bulk power services; DPS—More appropriate for distributed power services; BDPS—Adequate for either bulk or distributed power services. ^b Represents the round-trip efficiency for energy storage applications (electricity-to-hydrogen-to-electricity), not the direct production efficiency of electrolysis.

Although geographically dependent, pumped hydro energy storage (PHS) systems are widely used and cost-effective. PHS systems, which can operate with up to 85% of round-trip efficiencies and have lifespans of up to 60 years, are the only cost-effective storage technology, representing about 99% of global energy storage capacity [61,65]. There are 11,749 sites in Colombia with a capacity for PHS systems between 2 and 150 GWh, with a capacity to store 319,484 GWh for 6 or 18 h at full capacity [71].

Moreover, electrochemical batteries with the capacity to store energy and provide 4 to 10 h of electricity are the best alternative to PHS, which has been widely available but limitedly applied in some locations worldwide because of its high CAPEX and LCOE.

Based on technology readiness level and availability, this study considers using pumped hydro energy storage systems with 85% efficiency [65], costing 3008 USD/kW, and Li-ion batteries costing 2222 USD/kW [57].

2.4.3. Industrial Heat Demand

Limited technologies are available to replace fossil-based industrial heat demand, a significant and essential challenge to curve industrial carbon emissions and meet the net-zero carbon emission goals [72]. Thermal energy systems (TES) is a new clean technology developed to store energy to provide dispatchable electricity and heat at up to 1500 °C to 1700 °C at low costs, and are projected to reduce electric heating costs by 50% to 63% and support up to 90% of the industrial heat demand [73].

Likewise, TES can store heat and electricity at a low cost on the gigawatt scale and could be instrumental in meeting the under 2 °C rise in the global average temperature

target [74]. In the United States, some 75% of the industrial heat demand is required under 1000 °C, while 18% is already electrified [73]. Antora TESs with up to 39% round-trip efficiency for electricity, some 90% heat efficiency, and 400 to 750 USD of CAPEX can produce dispatchable heat up to 1500 °C [75,76].

Hydrogen production is another alternative that could support the demand for industrial heat and biofuel for transport energy. Alternative heat sources must be competitive alternatives to fossil fuels at small, medium, and large scales [72,77]. This study considers TESs and hydrogen as alternatives for heat supply in industry. Additionally, hydrogen is regarded as an alternative for transport. Hydrogen production requires electrolyzers with 63% to 70% hydrogen efficiencies and 2860 USD/kW of CAPEX [78].

2.4.4. Electric Transport

The transport sector is increasingly investing in developing clean energy technologies to tackle GHG emissions [79], chiefly recommending electric transport [80]. EVs operate with higher efficiencies (i.e., 60 to 80%) than internal combustion vehicles (i.e., 20 to 35%) [81]. Some studies indicate that switching from internal combustion vehicles to EVs can increase energy security [82] while reducing GHG mitigation costs [83]. However, the specialized literature shows contradictory results, with some studies showing that EVs outperform internal combustion vehicles, while others conclude the opposite [79].

EVs require over six times more minerals than conventional vehicles, including critical minerals like lithium, copper, or chromium [9]. The rising demand for critical minerals is forecasted to drive a shortage in the future, posing an energy security risk that will affect the costs of energy transition technologies [9].

Furthermore, the increasing presence of EVs will drive significant growth in electricity consumption, challenging power grids to adapt to growing peak demands related to EV charging patterns [84], which, added to other peak demands, might increase up to 20% the demand for power-generation capacity in the electric grid [85]. Integrating renewable energy sources and deploying energy storage technologies is essential to prevent the higher use of fossil fuels because of the higher use of EVs [84].

2.4.5. Biofuels

Transitioning from gasoline and diesel to ethanol and biodiesel mixtures in transport is a logical step toward cleaner and renewable energy sources, and reducing GHG emissions [86]. However, this must be carefully assessed since biofuels can have a carbon footprint larger than that of fossil fuels [87].

Ethanol can be used in mixtures of 5 to 15% in conventional gasoline vehicles, up to 85% in flexible fuel vehicles, or 100% in specially designed vehicles [55]. Moreover, biodiesel mixtures from 6 to 20% can be used in diesel engines [88,89], while 100% biodiesel is only possible in specially designed engines.

In Colombia, the national biofuel policy enforced ethanol and biodiesel mixtures [90]. In the country, biofuel production is supported by the production of ethanol in the sugar industry and biodiesel in the palm oil industry [91–94]. In total, 11.5% of ethanol production is used in ethanol-gasoline mixes, while 3.2% of crude palm oil is used for biodiesel production for biodiesel-diesel mixtures [95]. Table 3 shows the production of sugarcane and oil palm in Colombia, which uses some 2.6 million ha in total.

Table 3. Sugarcane and palm oil production in 2022 (Source: elaborated with data from [91,95–97]).

Crop	Area (ha)	Biofuel	Units	CAPEX (USD/t)
Sugarcane	2,078,591	40,000,000	L	165
Palm oil	576,799	685,694	t	49

The crude palm oil yield makes it possible to produce 28.9 GJ/ha of biodiesel per year [86], and, additionally, can yield an electricity surplus of 115 kWh per tonne of crude palm oil (CPO) [97]. In contrast, C-molasses (a byproduct of sugar production) can annually yield 46.6 GJ/ha of ethanol [86]. Moreover, sugarcane juice used for ethanol production (i.e., without sugar production) yields 214.3 GJ/ha. In contrast, the biomass byproducts can generate 185 kWh of surplus electricity per ton of sugarcane milled [96].

2.4.6. Wind and PV Potentials

The highest wind and PV potentials in Colombia are in the north of the department ‘La Guajira’ and on the Atlantic coast of Santa Marta, Barranquilla, and Cartagena. Using a best-case scenario approach, ‘La Guajira’ and the Atlantic coast are considered in the scenario calculations to assess the potential implications of the energy transition.

‘La Guajira’, with 20,848 km², accounts for 1.8% of Colombia’s territory and 20% of the national indigenous population [98]. This region has solar radiation between 4 and 6.5 kWh/m²/day, onshore wind velocities averaging 8 to 12 m/s at 80 m high, and offshore wind velocities over 15 m/s [98]. Remarkably, the onshore wind potential in ‘La Guajira’ amounts to 25 GW [99]. Exploiting 30% of PV potential in ‘La Guajira’ has a yearly potential of some 165.63 TWh of electricity, while the onshore and offshore wind potentials account for 477.15 TWh and 519.57 TWh, respectively [98]. Moreover, the offshore wind potential in the Atlantic coastline has an exploitable potential of some 50 GW [100,101].

The performance of wind systems was simulated in Renewable Ninja, a system funded by the Grantham Institute at Imperial College London and the Engineering and Physical Sciences Research Council [102]. PV systems and VESTAS 9.5 MW wind turbines (Vestas Wind Systems A/S, Aarhus, Denmark) were considered in the simulation for power capacities of 10 to 30 GW for either wind or PV systems.

Figure 6 shows the simulated performance of wind and PV systems in the upper Guajira for 10 GW of power. The results highlight the large variability of the power output throughout the year for wind and PV systems. The wind system operates with 57% availability, with similar outputs for offshore and onshore simulations, showing a significant reduction in production between September and December. Moreover, PV systems operate with an availability of 17%, with a lower electricity output between May and November than between December and April. Overall, these results stress the importance of storage systems in balancing supply and demand in the electric grid.

The yearly electricity potential as a function of the installed generation capacity, depicted in Figure 7, was defined, correlating the simulation results for different installed capacities.

The correlation in Figure 7 is used for onshore and offshore wind systems. Wind systems have three to four times the potential of PV systems, which is explained by the difference in availability. Therefore, one GW of wind power yields more electricity than one unit of PV power.

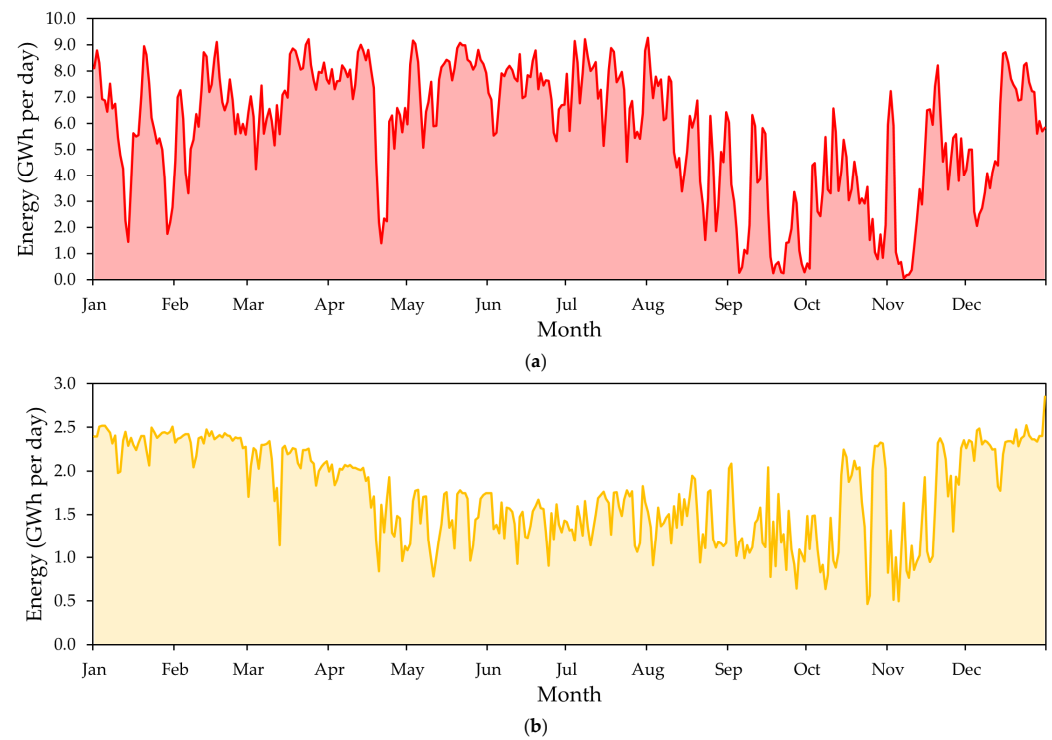


Figure 6. Estimated average daily electricity output from 10 GW of power installed in the upper Guajira: (a) Wind systems; (b) PV systems (source: own elaboration with data from [103]).

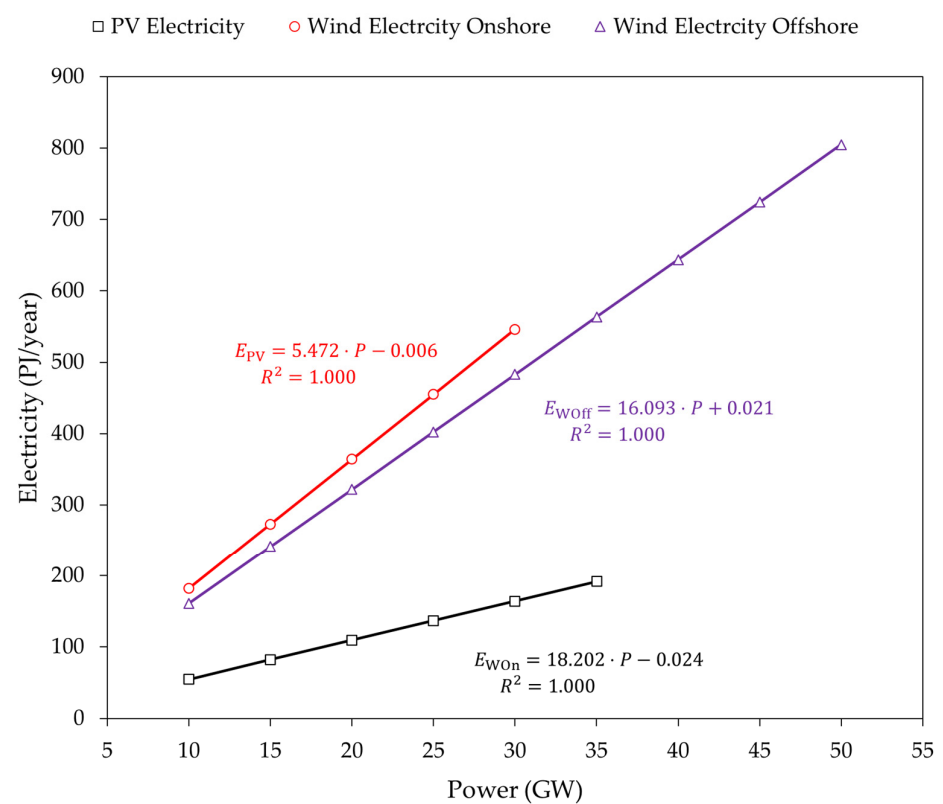


Figure 7. Ratio of electricity output to installed wind power in La Guajira (source: own elaboration with data from [103]).

Based on wind and solar availability, the implementation of PV and wind systems was prioritized in the following order:

1. Wind onshore: Implementation of onshore wind turbines up to 25 GW.
2. PV systems: Implementation of PV systems up to 25 GW.
3. Wind offshore: Implementation of offshore wind turbines up to 50 GW.

3. Materials and Methods

The analysis combines techno-economic data from international benchmarks with resource potential data specific to Colombia. Due to the limited availability of detailed, public data for local projects, the parameters for energy technologies studied (e.g., CAPEX, efficiency, lifespans) are based on widely used global sources and literature values.

3.1. Scenarios

While the Colombian government has outlined its strategic priorities, it has not yet published official, detailed energy transition scenarios. Therefore, to evaluate the implications of these goals, this study has developed four distinct analytical scenarios based on the administration's key policy directions—namely the focus on energy communities, transport electrification, green hydrogen production, and the expansion of wind and PV systems:

1. Baseline scenario: 2021 national energy balance.
2. 2035 projected energy balance: This scenario considers using biofuel to support transport and renewable electricity from biomass, PV, and wind systems to complement hydroelectricity in the electricity mix and support industrial heat.
3. 2035 projected energy balance: This scenario considers using hydrogen to support transport, industrial heat, and renewable electricity from wind and PV systems to support the remaining energy demand.
4. 2035 projected energy balance: Using renewable electricity to support the national energy demand.

These scenarios consider the transition of the sectors with the highest energy consumption in the country (i.e., transport, industry, residential, and commerce and public sectors) that accounted for 88% of the final energy consumption in 2021 [23]. Some demands, like jet fuel, which are difficult to replace with renewable alternatives, are excluded from the transition assessment (i.e., the demand for jet fuel projected by the government is kept in the transition scenarios discussed).

3.2. Scenarios Methodology

The scenario analysis was conducted using a deterministic, techno-economic model developed in Microsoft Excel. This model integrates the energy generation and storage parameters derived from the simulations with the techno-economic data for each technology to quantify the requirements for each energy transition pathway.

To establish a realistic baseline for the energy generation potential of variable renewable sources, this study simulated the performance of wind and PV systems in the region with the highest resource potential in Colombia, 'La Guajira'. The energy generation profiles were simulated using the Renewables Ninja platform, a tool developed by the Imperial College of London researchers [102,104].

For the wind simulations, VESTAS 9.5 MW turbines (Vestas Wind Systems A/S, Aarhus, Denmark) were used as the reference technology for both onshore (WOn) and offshore (WOff) scenarios. The simulations for all technologies (PV, WOn, and WOff) were run for a range of installed capacities, typically from 10 GW to 30 GW, to assess performance

at scale. The primary output of these simulations was the hourly energy generation data for a full year, which was then used to derive key parameters for the study.

From this data, the effective availability factors were calculated, resulting in approximately 57% for wind systems and 17% for PV systems. Crucially, the simulation results were used to establish the linear relationships between installed capacity (in GW) and total annual electricity generation (in PJ), as shown in Figure 7. These specific correlations were then employed as direct inputs in the main scenario analysis to calculate the required generation capacity.

Furthermore, to address the intermittency of these sources, the required energy storage for each scenario was calculated using the empirical, non-linear relationships presented in Figure 5. These correlations define the necessary Energy Storage Capacity (ESC) and Energy Storage Power Capacity (ESPC) as a function of the percentage of electricity generated by wind and PV (WPV) in the grid.

For the biofuels sub-model, the required land area for sugarcane and oil palm cultivation was calculated based on the energy demand of each scenario, using the energy yield factors (in GJ/ha) presented in Section 2.4.5. The baseline data for current national production and cultivated areas were sourced from official Colombian statistics provided by Agronet [91] and the National Federation of Biofuels [95]. Furthermore, the potential for surplus electricity co-generation from biomass byproducts was calculated using technical parameters from specialized literature, specifically the IRENA report for sugarcane [96] and Ramirez-Contreras et al. for palm oil [97].

The estimated land needed to produce enough biodiesel and ethanol to support 100% of the energy demand for road transport is calculated as follows:

$$L_i = \frac{TFD_j}{BY_i} \quad (3)$$

where

L_i —Land demand for crop i based biofuel (ha);

TFD_j —Road transport fuel demand for fuel j (PJ);

BY_i —Biofuel yield from crop i (PJ/ha).

Biofuel production will result in the production of biomass byproducts that have an electricity surplus potential, which is calculated as

$$E_i = L_i \cdot ES_i \cdot (1 - TL) \quad (4)$$

where

E_i —Surplus electricity potential from crop i (PJ);

ES_i —Electricity surplus potential from biomass byproducts from crop i (PJ/ha);

TL —Transmission loss in the national electric system.

The electricity needed to support the demand for industrial, residential, or commercial heat is calculated as

$$Q_{heat} = \sum_i \frac{Q_i \cdot \eta_{heat_i}}{\eta_{CH_j}} \quad (5)$$

where

Q_{heat} —Electricity to support heat demand (PJ);

Q_i —Energy needed to support the heat demand in sector i (PJ);

η_{heat_i} —Average national efficiency of the use of heat applications in sector i ;

η_{CH_j} —Efficiency of electric heat technology j .

Moreover, the hydrogen demand for transport and industrial heat is calculated as follows:

$$H_{transport} = \frac{TFD \cdot \eta_{comb}}{\eta_{electrolizer}} \quad (6)$$

$$H_{heat} = \frac{Q_i \cdot \eta_{heat}}{\eta_{electrolizer}} \quad (7)$$

where

$H_{transport}$ —Hydrogen demand for transport (PJ);

H_{heat} —Hydrogen for industrial heat (PJ);

TFD —Fuel demand for road transport (Gasoline + Diesel) (PJ);

η_{comb} —Average national efficiency of combustion engines;

$\eta_{electrolizer}$ —Efficiency of electrolyzer (70%).

Finally, the power demand for heat storage and hydrogen systems is calculated as follows:

$$P_i = \frac{H_i \cdot 10^6}{t \cdot \tau} \quad (8)$$

where

i —Hydrogen energy or industrial heat;

P_i —Power capacity of heat batteries or hydrogen production systems (GW);

t —Time in a year (86,400 s);

τ —System availability (0.7 for hydrogen production and heat supply).

3.3. Systems' CAPEX Calculations

The total CAPEX presented in this study is derived from the unit costs of the individual technologies using the following equations:

$$CAPEX_{P_i} = P_i \cdot UC_{P_i} \quad (9)$$

$$CAPEX_{B_i} = M_i \cdot UC_{B_i} \cdot 10^{-6} \quad (10)$$

where

$CAPEX_{P_i}$ —Total capital expenditure for power-based system i (million USD);

$CAPEX_{B_i}$ —Total capital expenditure for biofuel system i (million USD);

P_i —Required capacity for power-based system i (GW);

M_i —Required annual production for biofuel system i (t);

UC_{P_i} —Unit capital expenditure for power-based system i (USD/kW);

UC_{B_i} —Unit capital expenditure for biofuel system i (USD/t).

Table 4 details these specific unit CAPEX values, which serve as the primary inputs for the economic analysis of each scenario. These values are based on established international benchmarks as cited throughout the manuscript.

Table 4. Systems' unit CAPEX (source: elaborated with data from [57,76,78]).

System	Category	Unit CAPEX
Biodiesel (BioD)	Power	49 USD/t _{BioD}
Ethanol (Eth)	Power	158 USD/t _{c-capacity}
Heat Batteries (HB)	Storage	575 USD/kW
Hydrogen Storage (HS)	Storage	2860 USD/kW
Photovoltaic (PV)	Power	1909 USD/kW
Pumped hydro energy storage (PHS)	Storage	2640 USD/kW
Wind Offshore (WOff)	Power	3502 USD/kW
Wind Onshore (WOn)	Power	1540 USD/kW

4. Results

While the government projects a rapid transition to renewables, with a clear intention to accelerate the implementation of wind and PV systems, satisfying the energy demand projected for 2035 is essential for the country's stability and development and must not be overlooked. Therefore, scenarios 2, 3, and 4 discuss different technologies and energy sources based on the increased use of renewable energy in the end-use energy mix projected for 2035.

Figure 8 depicts the Colombian energy balance (i.e., scenario 1) and potential energy transitions in scenarios 2, 3, and 4 to meet the projected energy demand with renewables.

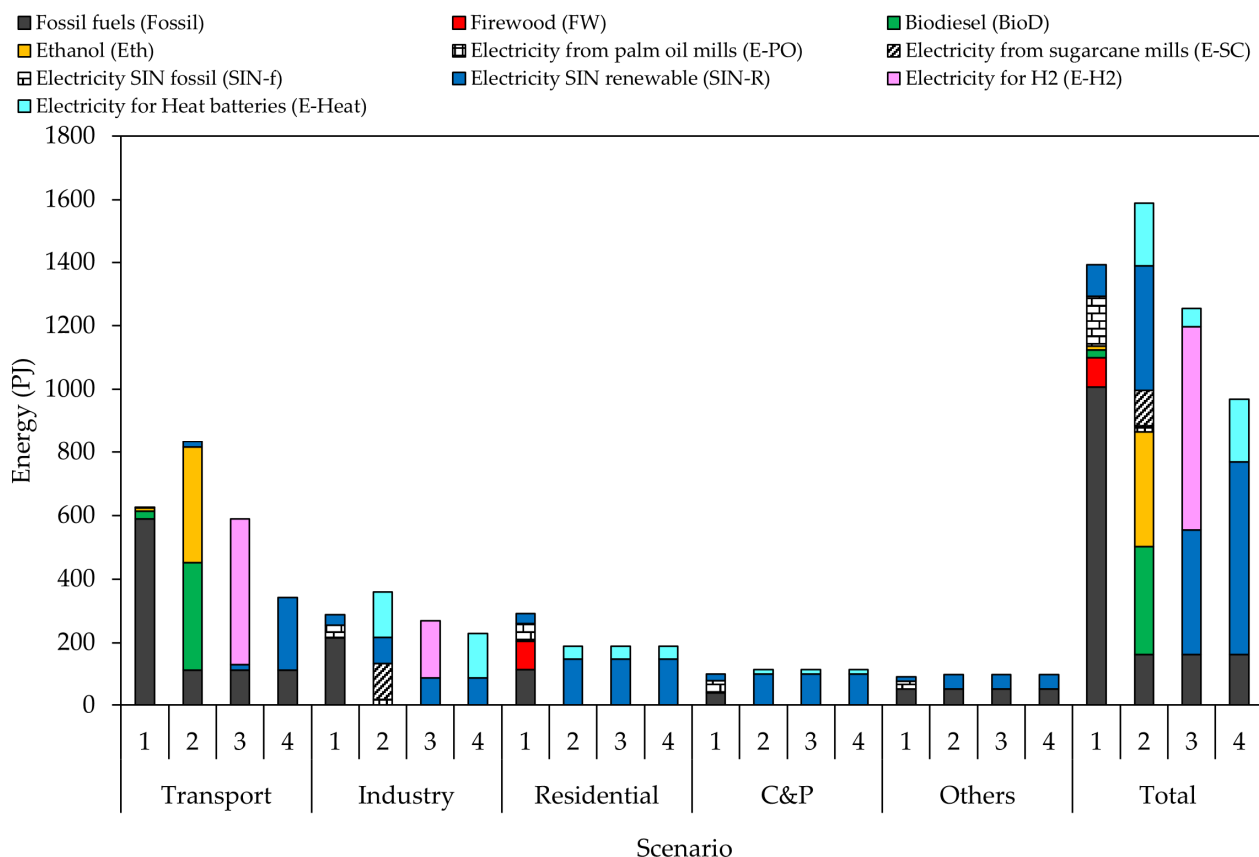


Figure 8. Summary of energy demand scenarios.

Scenario 1, with end-use energy of 1392 PJ, depicts the current high dependence on fossil fuels, as discussed in Figure 1 and C&P: Commercial and Public.

Figure 2 highlights the high demand for firewood in the residential sector. In contrast, Scenario 2 demands 1589 PJ of end-use energy. In this scenario, replacing 721.4 PJ of fossil fuels with biofuels in the transport sector needs an estimated increase from 0.6 to 12.3 million ha of palm oil to support the production of 340.2 PJ of biodiesel (i.e., to replace diesel in transport). Furthermore, sugarcane crops should increase from 1.7 to 3.8 million ha to support the production of 364.1 PJ of ethanol (i.e., to replace gasoline and natural gas in transport). The demand for aviation fuels will remain, and fossil fuels will be used in all scenarios. Biofuel production can increase surplus electricity from biomass by up to 18.5 PJ in palm oil mills and up to 112.3 PJ in sugarcane plants (i.e., considering greenfield technologies).

However, expanding palm oil crops and biodiesel production infrastructure by some 21 times appears unrealistic. In contrast, doubling sugarcane and ethanol production seems more feasible and should be assessed more thoroughly. Replacing fossil fuels with

electricity to support the heat demand in the industrial, residential, and commercial and public sectors demands to increase end-use electricity 1.5 times more than projected by the government for 2035. Surplus electricity from sugarcane mills could contribute to 19% of the electricity demand in this scenario.

Scenario 3, needing 1255 PJ of energy, demands 2.8 times more electricity than forecasted by the government for 2035, of which 59% is required for hydrogen production to support transport and industrial heat demand. Finally, scenario 4, with an end-use energy demand of 969 PJ, requires 2.1 times more electricity than projected by the government.

Scenario 2 requires more energy and less electricity than scenarios 3 and 4, which need more infrastructure for electricity transmission and distribution. Using biofuels for transport demands less technological and infrastructure improvement than hydrogen and electric vehicles in scenarios 3 and 4. The lower energy demand in scenarios 3 and 4 is because of the higher efficiency of alternative technologies considered as electric vehicles. These characteristics impact the demand for new renewable electricity generation systems and the use of energy storage when implementing wind and PV systems.

Figure 9 shows the demand for new power generation to meet the electricity demand and the energy storage needed in scenarios 2, 3, and 4. The storage demand was calculated with Equations (6) and (7).

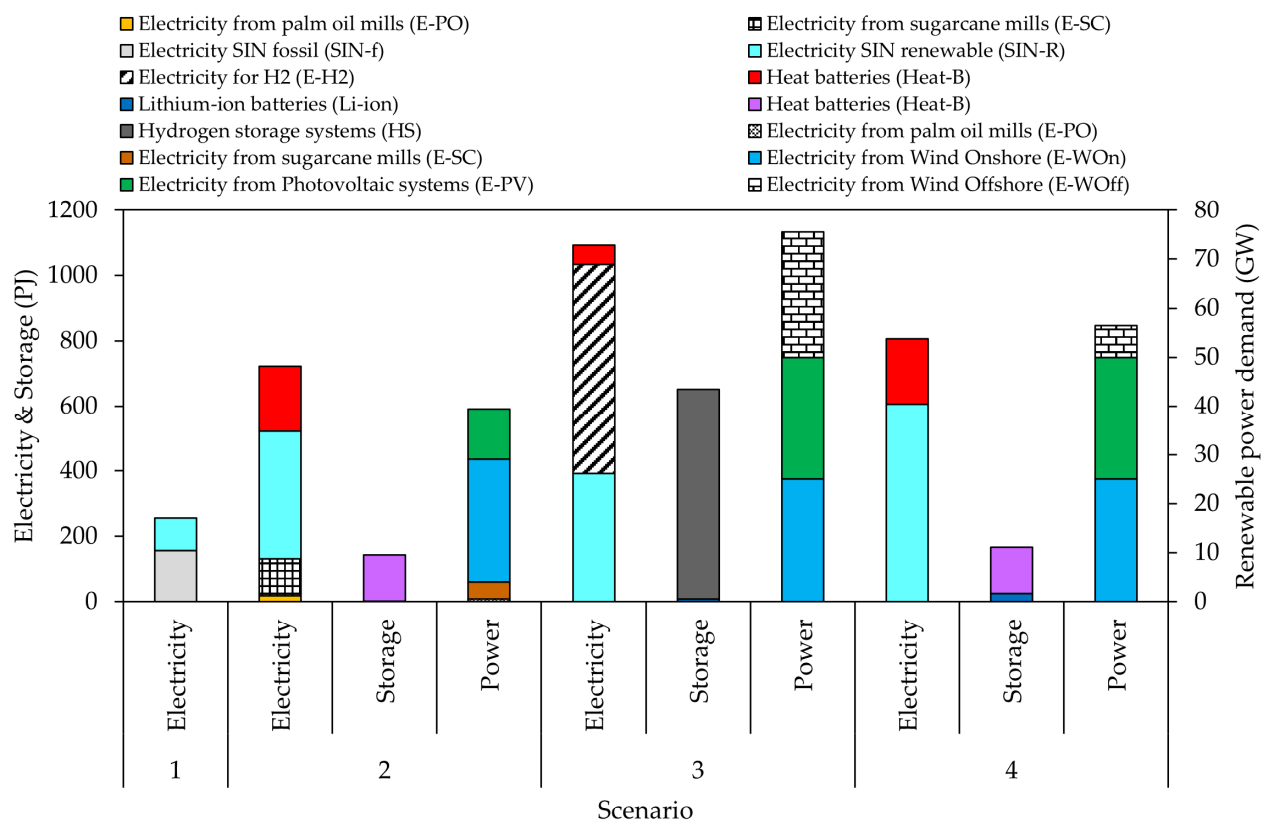


Figure 9. Electricity, storage, and new power generation in the energy transition scenarios.

Overall, biomass systems yield some 30 PJ/year of electricity per GW installed, wind systems yield up to 18 PJ/year, and PV systems generate around 5 PJ/year. This highlights the lower availability of wind and PV systems compared to systems with controllable output, like biomass in sugarcane plants.

Scenario 2 needs 39 GW of new power generation systems to complement the generation of 723 PJ of electricity, of which 10% are from biomass systems and 90% from wind onshore and PV systems. In this case, using 35.4 GW of PV and wind demands 142 PJ

of heat battery systems to guarantee dispatchable heat in industry and 1.9 PJ of PHS or Li-ion storage to balance the generation and demand of 162 PJ of electricity. The rest of the electricity is generated in hydraulic or biomass systems available in the national electric systems and does not need storage. In this scenario, biomass generation systems reduce the demand for storage systems.

The use of large hydroelectric plants to balance wind and PV output in the electricity system could accommodate the variability of wind and PV systems by reducing their production to balance the input from PV and wind without energy storage, which could be considered to reduce or eliminate the need for storage systems. However, this is challenging at best and needs further discussion and new policies. Moreover, extreme events like 'El Niño' will impact the capacity to use hydroelectric plants to accommodate wind and PV electricity outputs, potentially affecting the economy and society. Thus, energy storage systems are considered to operate in scenarios 2, 3, and 4.

In contrast, scenario 3 requires 75.6 GW of PV and wind systems (i.e., 33% wind onshore, 33% PV, and 34% wind offshore) to complement a demand of 1093 PJ of electricity, of which 643 PJ are needed for hydrogen production. Higher dependence on PV and wind systems drives the need for 9 PJ of PHS or Li-ion storage to balance the electricity generation and demand of 293 PJ. Furthermore, scenario 3 needs 643 PJ of hydrogen production and storage capacity.

Finally, scenario 4 needs 56.5 GW of PV and wind systems (i.e., 44% wind onshore, 44% PV, and 12% wind offshore) to support the electricity demand. Like scenario 2, supporting heat supply in the industry needs 142 PJ of heat battery systems. In comparison, wind and PV systems require an estimated 25 PJ of PHS or Li-ion storage systems to balance the generation and demand of 508 PJ.

Figure 10 shows the CAPEX needed in scenarios 2, 3, and 4. The CAPEX for hydrogen production only considers the CAPEX of hydrogen production systems while omitting hydrogen storage systems. In this case, the figure presents the results for PHS systems because, while Li-ion batteries have a slightly lower CAPEX (i.e., 2222 USD/kW compared to 2640 USD/kW), PHS has a lifespan of 60 years, contrasted with 10 years for Li-ion batteries.

The results show that new power systems need from 66 to 95.5% of the CAPEX, depending on the scenario. Scenario 2 needs 95.5% of the CAPEX, estimated at nearly 144 billion USD, for biofuels, wind, and PV systems, while 4.5% is required for PHS and heat battery systems. This investment represents 4.2 times the 34 billion USD projected by the government and 42% of the Colombian GDP. In this scenario, the investment in biofuel production accounts for 54% of the CAPEX and provides 53% of the energy in the scenario (44% as biofuel and 8% as electricity). Moreover, wind and PV require 46% of the CAPEX to provide 27% of the scenarios' energy (100% as electricity).

Moreover, scenario 3 needs a CAPEX estimated at some 267 billion USD, of which hydrogen production systems require 31% of the CAPEX (in this case, hydrogen storage systems were not included in the assessment). Overall, wind and PV systems for electricity generation account for 66% of CAPEX to provide 75% of the energy demanded. The CAPEX in this scenario coincides with some 77% of the national GDP and nearly 8 times the investment projected by the government.

Finally, scenario 4 demands a CAPEX estimated at some 123 billion USD (i.e., about 36% of the national GDP and 3.6 times the governmental projected investment). Wind and PV systems, in this case, account for 88% of the CAPEX and provide 67% of the scenarios' energy, while storage systems account for 12%.

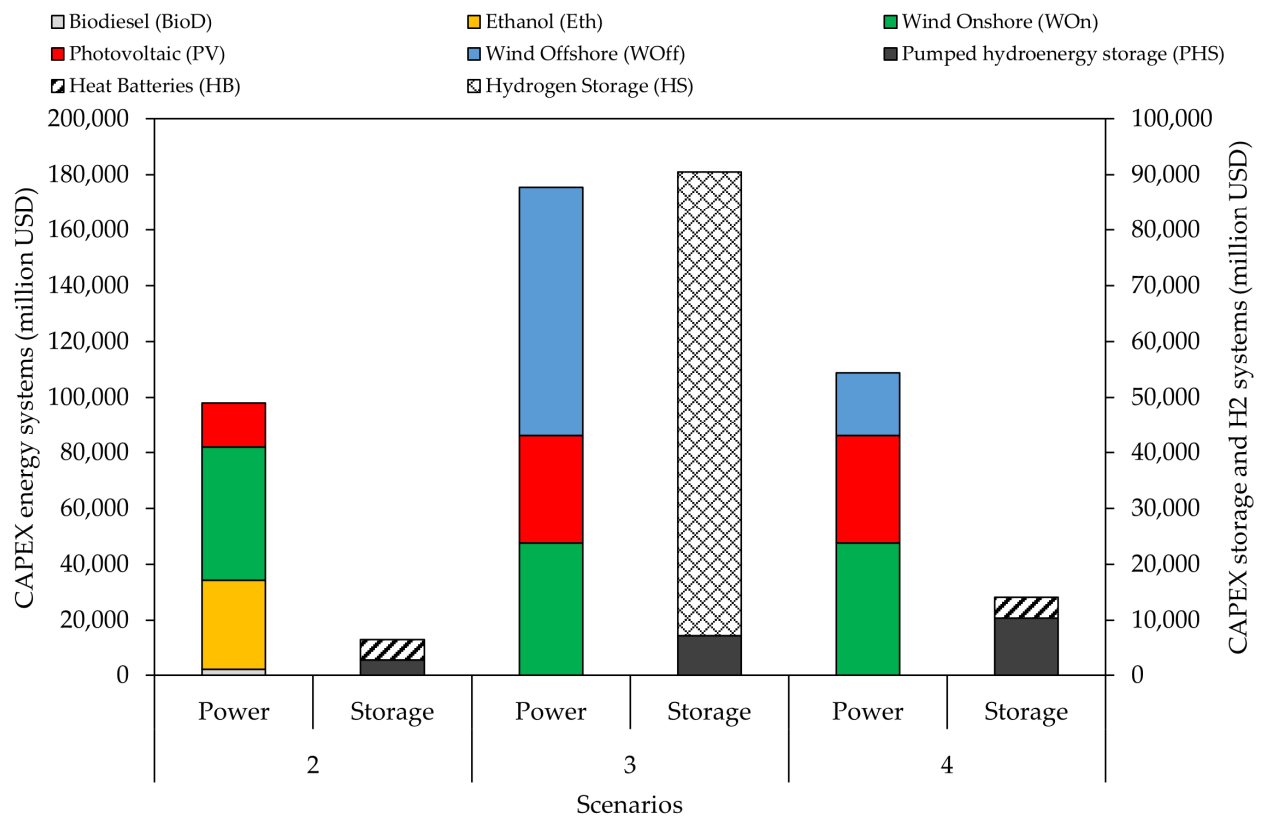


Figure 10. CAPEX required for power and storage demand per scenario.

A preliminary calculation shows that implementing the scenarios in a 10-year period (which is not as rapid as the government would like) requires a yearly investment of 4% to 8% of the national GDP, which coincides with 3 to 8 times the governmental projections to invest in the energy transition.

5. Discussion

5.1. Principal Findings

The central finding of this study is the stark economic infeasibility of Colombia's accelerated energy transition as currently envisioned. Our scenarios reveal that a transition dominated by wind and PV systems demands a capital investment that is 3.6 to 7.8 times higher than the government's 34 billion USD projection. This immense investment gap is further exacerbated by the pre-existing barriers outlined in Section 2, such as the lack of grid infrastructure and high initial costs [30], which would likely inflate final project expenditures even beyond these estimates.

To illustrate this further, the projected implementation of new wind systems in 'La Guajira' requires between 654 km and 1632 km of new transmission lines at an estimated cost of up to 3.5 billion USD [33]. This substantial investment gap is not unique to Colombia and exemplifies the challenges highlighted in the literature for other emerging economies, where high financing costs and the need for robust financial development to mitigate risk are primary barriers to attracting the necessary long-term capital [11,13].

Furthermore, our analysis confirms that green hydrogen is currently economically prohibitive, a finding that directly challenges its role as a near-term decarbonization solution. When contrasting the high costs and intermittency of the VRE-focused scenarios, the alternative national energy potentials described in Section 2 become highly relevant. The country's significant, albeit politically complex, potential in hydroelectricity [45] and biomass [30]

offers pathways that could provide more stable and potentially more cost-effective energy, warranting their re-evaluation in a truly pragmatic national energy strategy.

5.2. Study Limitations

It is important to acknowledge the limitations of this study, which provide avenues for future research. First, our analysis relies on international techno-economic benchmarks for cost and performance data. While this is a standard practice when local data is scarce, country-specific costs could alter the final investment figures. Second, this study employs a deterministic, static CAPEX analysis for 2035. It does not include a sensitivity analysis to test the robustness of the results against variations in key assumptions, nor does it model the dynamic, year-by-year pathway of the transition, nor does it calculate the resulting LCOE, nor does it quantify the cost per tonne of CO₂ reduced for each scenario.

Finally, the techno-economic scope does not quantify critical socio-political barriers, such as community acceptance of large-scale projects or supply chain risks for necessary minerals.

5.3. Directions for Future Research

The limitations of this work highlight several critical directions for future research. A crucial next step is to conduct a comprehensive sensitivity analysis to understand which variables (e.g., hydrogen costs, interest rates) pose the greatest risk to the transition's feasibility.

Furthermore, developing a dynamic energy systems optimization model for Colombia would allow for analyzing least-cost transition pathways over time and their impact on the national LCOE. A crucial extension of this would be to conduct a detailed CO₂ abatement cost analysis to determine the cost-effectiveness of each scenario in terms of emissions reduction.

Research is also needed to develop a localized cost database for renewable technologies in the Colombian context and to model the specific grid infrastructure upgrades required to ensure stability with a high penetration of renewables.

Finally, socio-economic studies are needed to assess the political and community feasibility of the scenarios presented here.

5.4. Policy Implications and Recommendations

The results of this study carry substantial policy implications, primarily by highlighting the stark trade-offs between the government's ambitious decarbonization goals and the nation's pressing socio-economic priorities.

As established, Colombia's contribution to global GHG emissions is minimal, accounting for 0.5% [46], yet the scenarios analyzed would require diverting a substantial portion of the national GDP—between 4% and 8% annually. Such an investment would inevitably compete with resources needed to address deeply entrenched challenges, including post-conflict peace-building, poverty eradication, and improving access to essential services like healthcare and education, which are central to the nation's sustainable development. This trade-off amplifies the challenge of securing the foreign direct investment and low-cost financing identified as critical enablers for the energy transition [12].

For international investors, a nation diverting significant resources from core social and economic stability goals may represent a higher perceived risk, complicating the financial flows needed to fund the transition.

Furthermore, the findings underscore the political and economic complexities of a "just transition". The immense capital required for VRE-focused scenarios favors large, often international, developers, while the associated social and environmental costs are disproportionately borne by rural and marginalized communities, as exemplified by the

conflicts in ‘La Guajira’. Moreover, a policy focused solely on domestic consumption fails to address the “carbon leakage” problem, where fossil fuel production is merely diverted to export markets, nullifying global climate benefits. A coherent transition policy must therefore include a managed decline in fossil fuel production and exports, alongside robust benefit-sharing mechanisms to ensure equity.

Given the economic infeasibility of scenarios 3 and 4, a more pragmatic policy path is warranted. Our findings suggest that switching the transport and industrial sectors to 100% renewables is currently unfeasible, a conclusion reinforced when considering that even wealthier nations like those in the European Union average just 10.8% renewables in transport, ranging from 0.9% in Croatia to 33.7% in Sweden [47]. The analysis indicates that gradually increasing the share of liquid biofuels—globally recognized for their growth and compatibility with existing infrastructure [48]—is a more realistic near-term strategy for the transport sector. This should be complemented by demand-reduction policies, such as investing in less energy-intensive rail and waterway transport. For industrial heat, thermal energy systems present a viable technical alternative, but their feasibility hinges on securing a source of low-cost electricity, which is not currently available.

Finally, policymakers must re-evaluate the nation’s full portfolio of energy assets. Instead of over-relying on costly VRE and storage, a strategic pivot should consider the significant untapped potential of more cost-effective and stable resources. The country’s identified 51 GW hydroelectric potential [49], for instance, could meet the electricity demand of scenarios 2 and 4 at 40% to 65% of the projected CAPEX. Similarly, biomass resources can play a crucial role in providing decentralized energy solutions at local and regional levels [50]. A successful long-term strategy must be built on an economically viable medium-term plan that prioritizes proven, cost-effective technologies to pave a sustainable path for deeper decarbonization.

5.5. Challenges and Drawbacks of the Proposed Pragmatic Pathways

While the alternatives discussed above offer more feasible pathways than a rapid, high-cost transition, it is crucial to acknowledge their significant implementation challenges and drawbacks. Promoting biofuels, particularly ethanol from sugarcane, requires a careful assessment of land-use competition, which could impact food security and prices and lead to deforestation and biodiversity loss if not managed sustainably.

Furthermore, the lifecycle carbon footprint of biofuels, including emissions from cultivation and processing, must be rigorously evaluated to ensure a net climate benefit. Furthermore, the economic viability of these industries often relies on substantial government subsidies, and the intensive agricultural practices required can strain local resources through the heavy use of water, fertilizers, and fuel for farm machinery.

Similarly, while hydroelectric power offers stable, low-cost energy, its expansion faces significant socio-environmental hurdles. As exemplified by the challenges with the Hidroituango project, large-scale dams can lead to the displacement of communities, disruption of river ecosystems, and potential methane emissions from reservoirs. Overcoming the political and social opposition to new projects would require transparent governance and robust benefit-sharing mechanisms.

Furthermore, the heavy reliance on the high wind potential of the ‘La Guajira’ region presents significant socio-environmental challenges that could impede project implementation. This region is home to a large indigenous Wayuu population, and the development of large-scale wind farms has already generated conflicts related to land rights, the adequacy of community consultations, and the equitable distribution of economic benefits.

A truly “just transition” cannot be achieved if the burdens of development are borne by vulnerable local communities while the benefits (both economic and in terms of energy

access) flow elsewhere. Therefore, the techno-economic potential of ‘La Guajira’ must be weighed against the critical need for robust social-licence-to-operate frameworks, ensuring meaningful community participation and addressing the paradox of energy poverty in an energy-rich region.

Finally, proposing natural gas as a bridging fuel requires caution. Although less carbon-intensive than coal or oil, it is still a fossil fuel that produces greenhouse gas emissions. The risk of methane leakage throughout the supply chain can significantly diminish its climate advantages. Moreover, investing heavily in new gas infrastructure risks creating a “technological lock-in”, potentially delaying the eventual transition to a fully renewable system.

6. Conclusions

This study’s primary and unequivocal finding is the profound disconnect between the Colombian government’s ambitious energy transition goals and the nation’s current techno-economic reality. Our analysis reveals that achieving a near-total renewable energy matrix by 2035, driven primarily by variable wind and solar power, would require a capital investment of 123 to 267 billion USD—a sum equivalent to 36% to 77% of the nation’s 2022 GDP and 3.6 to 7.8 times the government’s own projections. Technologies like green hydrogen, while promoted, are particularly unfeasible at present, further widening this gap. This immense capital requirement demonstrates that the current roadmap is not only overly ambitious but economically untenable, posing significant risks to the country’s fiscal stability and energy security.

The challenges identified in Colombia offer a critical and generalizable lesson for other developing and energy-exporting nations. These countries face a difficult trilemma: the need to meet international climate commitments, the dependency on fossil fuel revenues for economic stability, and the urgent mandate to ensure affordable, reliable energy for their populations. Our findings serve as a cautionary tale against adopting idealized transition models that overlook fiscal constraints and national contexts. For these nations, a pragmatic and sequenced strategy is paramount. A transition paced by economic reality is not a failure but a necessity to avoid jeopardizing broader development goals and ensure the long-term sustainability of the shift itself.

Based on our findings, we propose a shift in policy from a rapid, high-cost overhaul to a gradual, strategic pivot that leverages Colombia’s intrinsic strengths. Rather than over-relying on capital-intensive variable renewables and their requisite storage, the most realistic path forward involves (1) maximizing the potential of established, cost-effective national resources, such as expanding ethanol production from the mature sugarcane industry and re-evaluating the extensive, untapped potential of hydroelectric power; (2) prioritizing investments in energy demand reduction through less energy-intensive transport modes like trains and waterways; and (3) strategically deploying natural gas as a bridging fuel to ensure stability while incrementally phasing in proven renewable technologies.

Ultimately, a successful energy transition is not defined by the speed of its promises but by the sustainability of its execution. For Colombia and nations in similar positions, the path to a decarbonized future must be paved with economic realism, strategic pragmatism, and a clear-eyed assessment of national developmental priorities.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Al	Alcohol
BDPS	Bulk or distributed power services
Bg	Bagasse
BioD	Biodiesel
BPS	Bulk power services
C	Coal
C&P	Commercial and public
CAPEX	Capital expenditures
CC	Chalk coal
CCUS	Carbon capture, use, and storage
Co	Coque
CPO	Crude palm oil
D	Diesel
DPS	Distributed power services
E	Electricity
EG	Electricity from the grid
E-H ₂	Electricity for H ₂
E-Heat	Electricity for Heat batteries
EP	Exports primary energy
E-PO	Electricity from palm oil mills
E-PV	Electricity from Photovoltaic Systems
ES	Exports of secondary energy
ESC	Energy storage capacity
E-SC	Electricity from sugarcane mills
ESPC	Energy storage power capacity
Eth	Ethanol
EV	Electric vehicles
E-WOff	Electricity from Wind Offshore
E-WOn	Electricity from Wind Onshore
FC	Final energy consumption
FO	Fuel oil
Fossil	Fossil fuels
Fw	Firewood
G	Gasoline
Ga	Gasoline
H	Hydraulic
HE	Hydro energy
Heat-B	Heat batteries
HS	Hydrogen storage systems
IL	Inefficiencies and losses
In	Inefficiencies
InP	Inventories primary energy

IP	Imports primary energy
IS	Imports of secondary energy
JF	Jet fuel
Ke	Kerosene
LCOE	Levelized cost of electricity
Li-ion	Lithium-ion batteries
LP	Loss of primary energy
LPG	Liquefied petroleum gas
LS	Loss of secondary energy
LT	Loss in transformation processes
NG	Natural gas
O	Other renewables
OPEX	Operational expenditures
Pe	Petroleum
PHS	Pumped hydro energy storage
Pr	Primary energy
Pro	Primary energy sources
PV	Photovoltaic
RP	Reinjection of primary energy
S	Secondary energy
SCP	Self-consumption of primary energy
SCS	Self-consumption of secondary energy
SG	Electricity generated for self-consumption in industry
SIN	National Interconnected System
SIN-f	Electricity SIN fossil
SIN-R	Electricity SIN renewable
SMR	Steam methane reforming
TES	Thermal energy systems
ThP	Thermal power plants Natural gas, fueled with coal, bagasse, diesel, petroleum, liquified petroleum gas, or fuel oil
TP	Primary energy used in transformation processes
TRL	Technology readiness level
TrP	Transfer primary energy
TrS	Transfer of secondary energy
TS	Secondary energy used in transformation processes
UE	Useful energy
VRE	Variable renewable energy
W	Wind
Wa	Waste
WOff	Wind Offshore
WOn	Wind Onshore
WPV	Wind and PV electricity

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