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On the Potential of Blue Hydrogen Production in Colombia: A Fossil Resource-Based Assessment for Low-Emission Hydrogen

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Abstract: Latin America is starting its energy transition. In Colombia, with its abundant natural resources and fossil fuel reserves, hydrogen (H_2) could play a key role. This contribution analyzes the potential of blue H_2 production in Colombia as a possible driver of the H_2 economy. The study assesses the natural resources available to produce blue H_2 in the context of the recently launched National Hydrogen Roadmap. Results indicate that there is great potential for low-emission blue H_2 production in Colombia using coal as feedstock. Such potential, besides allowing a more sustainable use of non-renewable resources, would pave the way for green H_2 deployment in Colombia. Blue H_2 production from coal could range from 700 to 8000 kt_{H_2}/year by 2050 under conservative and ambitious scenarios, respectively, which could supply up to 1.5% of the global H_2 demand by 2050. However, while feedstock availability is promising for blue H_2 production, carbon dioxide (CO_2) capture capacities and investment costs could limit this potential in Colombia. Indeed, results of this work indicate that capture capacities of 15 to 180 Mt_{CO_2}/year (conservative and ambitious scenarios) need to be developed by 2050, and that the required investment for H_2 deployment would be above that initially envisioned by the government. Further studies on carbon capture, utilization and storage capacity, implementation of a clear public policy, and a more detailed hydrogen strategy for the inclusion of blue H_2 in the energy mix are required for establishing a low-emission H_2 economy in the country.

Keywords: blue hydrogen; coal; CO_2 capture; Colombia; gasification

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1. Introduction

Energy demand keeps increasing due to economic growth, increasing population, and higher life standards. Indeed, ensuring access to affordable, reliable, sustainable, and modern energy for all is one of the 17 UN Sustainable Development Goals [1]. However, the energy sector is a major contributor to Greenhouse Gas (GHG) emissions, and the recent Intergovernmental Panel on Climate Change (IPCC) report has highlighted the urge for decarbonization of this sector [2]. Therefore, in Latin America, countries such as Chile, Uruguay, Brazil, Costa Rica, and Colombia have begun developing strategies to promote the energy transition in the region.

While most of the attention has turned towards renewable energy sources, such as solar and wind, the need to store electricity and integrate the locally available energy resources are smoothing the way for H_2 as an energy carrier. H_2 is a sought-after energy carrier because of its zero direct GHG emissions. Since pure H_2 is scarcely found in nature, though, the energy required for its production usually results in high indirect GHG emissions [3].

Thus, the quest for a cleaner energy source has led to low-emission H_2 (<4.33 gCO_2-eq/gH_2 [4]), either via water electrolysis using renewable energy sources (e.g., solar, wind, hydroelectric and biomass)—known as green H_2—or via fossil fuels (e.g., natural gas, coal, and oil) with carbon capture, utilization, and/or storage (CCUS)—known as blue H_2.

Currently, most H_2 is produced from fossil fuels (up to 98%), i.e., from natural gas and oil derivatives (75%), and from coal (23%) [5], almost entirely without CCUS [6,7], blue H_2 deployment being still in early stages, with recent reports marking it as only 0.6% of H_2 worldwide production [5–8]. In this context, less than 1% of Latin American renewable energy projects include low-emission H_2 production, and at least a decade might be needed to see large-scale green H_2 production in the region [8–10]. However, recent energy outlooks and environmental reports call for low-emission H_2 to comply with the pressing need for GHG emissions reduction [2,8,11–15]. Blue H_2 has, then, appeared as a transitory solution to supply the low-emission H_2 demand in the region, with most published H_2 strategies—Colombia's included—considering it an important stepping stone in the path to decarbonization [6,8,16–18]. In particular, the promotion of blue H_2 as a clean alternative considers that the large fossil fuel industry infrastructure could favor the implementation of the necessary CCUS technologies while continuing to take advantage of the local natural resources and reducing the impact of energy transition on employment in some countries. Colombia could benefit from this approach, due to its significant reserves of non-renewable resources and strong economic dependence on the oil and coal extraction [19,20].

H_2 in Colombia is currently both produced and demanded in majority by the refinery sector, and it is obtained through Steam Reforming of Natural Gas (NG), with a 90% gray H_2 and 10% blue H_2 mix [16,21]. The recently launched National Hydrogen Roadmap calls for the conversion of such gray H_2 to blue H_2 in the next decades, as well as the committment to significantly increase low-emission H_2 production in the country [16]. Although the roadmap mentions coal as potential feedstock for blue H_2, to the best of our knowledge, there are no current projects for H_2 production through coal gasification, in spite of the significant reserves of this mineral in the country [16,22,23]. Additionally, two scenarios of the National Energy Plan 2020–2050 (PEN 2020–2050) envision H_2 as part of the Colombian energy matrix for the energy transition, with an 11% H_2 share in the most ambitious one [24].

Some studies on the insertion of H_2 in the Colombian energy mix were performed in the early 2010s, and with the recent growing interest on H_2 as energy carrier around the world, new reports are appearing in this area [25–28]. Research on H_2 production potential in Colombia has been prolific in recent years, mainly considering the use of residual biomass, with diverse sources such as coffee and cacao plantations [29,30], Pinus patula [31], palm kernel and Jatropha [32,33], and sugarcane [34–36]. Studies on the production through ethanol steam reforming [37] and biomass gasification [38], as well as on energy production from H_2 [34,39], and on H_2 storage [40,41] have also been reported. Meanwhile, studies on Colombian potential for H_2 production from fossil fuels are scarce and mostly superficial with respect to coal as feedstock [25,42].

This work presents an analysis of the potential for blue H_2 production in Colombia, examining feedstock availability and main technical aspects. In addition, to get a more realistic assessment of this potential, the required investment and CO_2 capture capacity were compared with the investment envisioned by the government and the potential CO_2 storage capacity due to enhanced oil recovery operations in the country, respectively. Knowledge of such potential will allow the assessment of the role of Colombia as a player in the expected global H_2 market.

2. Methodology

A literature review for blue H_2 production and CCUS technologies was carried out. Among these, only well-established technologies were selected to assess Colombian potential in the upcoming decades. Calculations for potential blue H_2 production were based on fossil fuel reserves and annual production reported by government agencies such as *Unidad* *de Planeación Minero-Energética (UPME)* [23,43], *Agencia Nacional de Minería (ANM)* [22], *Agencia Nacional de Hidrocarburos (ANH)* [44], and *Ministerio de Minas y Energía* [45,46]. The amount of coal available for H_2 production was calculated from the projected decrease in worldwide demand under several scenarios, grouped as conservative, moderate, and ambitious. To ensure the same basis for comparison, data for the different scenarios were obtained from the comparative Global Energy Outlook reported by Resources for the Future, selecting the scenarios from Energy Outlooks published in 2020 and 2021 [47]. Table 1 shows the compared scenarios and their key assumptions.

Table 1. Compared energy scenarios and their key assumptions.

Type	Institution	Scenario	Key Assumptions
Conservative	Equinor [48]	Rivalry	Social, economic, and political tension strongly affect the energy market and energy transition. Energy policies privilege energy security rather than sustainability. Slow implementation of clean technologies and pollution reduction.
	OPEC [49]	Reference	Incorporates enacted policies and assumes some future policy changes.
Moderate	BNEF [50]	Economic Transition Scenario—ETS	Based on internal views on technological change, which drives the development of markets and business models. Consistent with 3.3 °C warming by 2100.
	Equinor [48]	Reform	Market and technology evolve similarly to recent trends. Policy trends follow current policy momentum. Economic growth is prioritized.
	BP [15]	Business as Usual—BAU	Policies, technologies, and consumer preferences evolve similarly to recent trends. Carbon emissions peak in mid-2020s. Little reduction in energy-based carbon emissions, emissions in 2050 being less than 10% below 2018 levels.
	IEA [12]	Stated Policies Scenario—STEPS	Considers enacted and announced policies, including climate targets. COVID-19 is gradually brought under control in 2021. Global economy returns to pre-crisis levels also in 2021.
	IRENA [51]	Planned Energy Scenario—PES	Based on current and announced policies. Considers NDCs in the Paris Agreement and long-term emissions reduction targets consigned in national energy plans and climate policies up to 2019.
Ambitious	BP [15]	Rapid Transition—RT	Considers policy measures led by a significant increase in carbon prices and supported by sector-specific measures (power, transportation, buildings, industry). A 70% reduction in energy-based carbon emissions by 2050. Consistent with limiting warming to "well below" 2 °C by 2100.
	IEA [12]	Sustainable Development Scenario—SDS	UN Sustainable Development Goals, including universal access to energy, reduced air and water pollution, as well as the Paris Agreement are achieved. Assumptions on public health and the economy are the same as in the STEPS. Consistent with 1.7–1.8 °C warming by 2100.
	IRENA [51]	Transforming Energy Scenario—TES	An "ambitious, yet realistic" scenario. Improved energy efficiency and large-scale renewables deployment. Limits warming to "well below" 2 °C and sets the path towards 1.5 °C by 2100.
	Equinor [48]	Rebalance	Ambitious policies push energy system towards limiting warming to "well below" 2 °C by 2100. World focus on achieving all UN Sustainable Development Goals. Reduction in the income gap in emerging economies, and more focus on well-being in industrialized countries.

Table 1. *Cont.*

Type	Institution	Scenario	Key Assumptions
	BP [15]	Net Zero—NZ-BP	Trends from the Rapid Transition scenario are enhanced by substantial societal changes. A 95% reduction in energy-based global carbon emissions by 2050. Consistent with limiting temperature rises to 1.5 °C by 2100.
	IEA [52]	Net Zero—NZ-IEA	Intended to show what/when is needed to achieve net-zero energy-related and industrial process CO_2 emissions by 2050. Consistent with limiting long-term warming to 1.5 °C.

Reduction in global coal demand under each scenario was calculated as a percentage, using 2019 global coal demand data as reference value. Given that most Colombian coal is destined to overseas markets, the underlying assumption was that Colombian coal exports would decrease in the same proportion as global coal demand, and thus, coal not exported due to such a decrease could be used in Colombia for H_2 production.

Constant annual production of 84.5 Mt coal was assumed in accordance with the recent trend (excluding 2020) [23,53], 20% of which was considered to be reserved for internal use. The remaining 80% (67.6 Mt) was considered the export basis, such that coal available for H_2 production in Colombia under each scenario was calculated by applying the decrease percentage to this export basis.

To calculate the amount of H_2 to be produced from the available coal, a factor of 0.131 kg_{H_2}/kg_{coal} was used, as reported by the CCS Institute for typical coal gasification processes with CCS [54,55]. The amount of CO_2 to be captured in such H_2 production was calculated considering 22 kg_{CO_2} to be captured per kg_{H_2} produced, a value also reported for typical coal gasification processes by the CCS Institute [54,55]. Emerging H_2 production processes, i.e., underground coal gasification [56] or plasma gasification [57], were not considered for these estimations. Demand and market projections were obtained from technical reports [58,59] and international energy outlooks [47,51,52], Colombia's Energy Plan 2020–2050 [24], and Colombia's National Hydrogen Roadmap [16].

A rough investment cost estimate was made with the use of reported techno-economic data for coal-based H_2 production. Sgobbi et al. [60] reported techno-economic data for several H_2 production methods, including coal gasification. The authors considered centralized H_2 production, in medium- and large-scale plants (440 and 1667 MW, respectively), with and without CCS [60]. Costs were reported in 2010 Euros (EUR_{2010}), with values for 2015 and projections for 2030 that account for technology learning factors [60]. Based on the reported value for large-scale coal gasification plants with CCS, estimations of the investment required to meet three of the studied scenarios (Reference-OPEC—conservative, BAU-BP—moderate, and Net Zero-BP—ambitious) were obtained. Given that currently there are no operating plants of this kind, production was assumed to start in 2030 and, hence, the investment cost projected to 2030 was used (363.25 EUR_{2010}/kW [60]). The number of large-scale plants required to meet the projected H_2 production under each scenario was obtained by dividing the projected production by the large-scale plant capacity (1667 MW [60]). The required investment was calculated by multiplying the number of large-scale plants required to meet the demand by the cost of one large-scale plant (605.54 M.EUR_{2010}). The values were converted to USD with the aim of comparing the required investment to the expected investment, as reported in Colombia's Hydrogen Roadmap [16]; a factor of 1.33 USD/EUR was used, corresponding to the average USD/EUR exchange value in 2010 [61].

3. Results and Discussion

3.1. H_2 Production from Fossil Fuels

Fossil fuels, traditionally used in direct combustion, can be used to produce blue H_2 and energy through technologically mature processes, see Figure 1. Standardized technologies produce syngas from each fossil feedstock and then follow a single path to

H_2, while emerging technologies do not require the syngas production stage [57,62–64]. Colombian fossil fuel reserves are included in the figure as a starting point for the potential transformations [43,45,46].

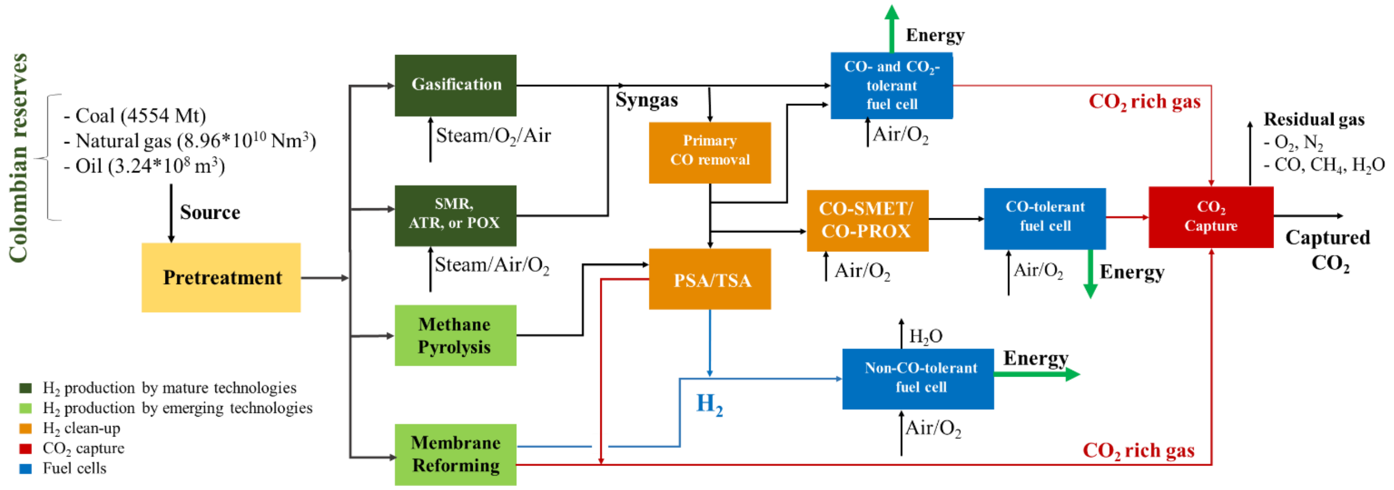

Figure 1. H_2 and H_2-derived energy production pathways from fossil fuels. Simplified process diagram. SMR: Steam Methane Reforming, ATR: Autothermal Reforming, POX: Partial Oxidation, PSA: Pressure Swing Adsorption. TSA: Temperature Swing Adsorption, CO-SMET: Selective CO methanation, CO-PROX: Preferential oxidation of CO.

H_2 from NG can be produced through Steam Methane Reforming (SMR), Autothermal Reforming (ATR), and Partial Oxidation (POX) processes [57,62,63], or through the emerging Membrane Reforming (MR) [65,66] and Methane Pyrolysis (MP) [64,67] processes. SMR is the most deployed technology, accounting for 48% of worldwide H_2 production and 95% of US production [6,68]. ATR and POX are also mature technologies but less extended since the need for pure oxygen increases their cost and complexity [62,69,70]. Nonetheless, the potentially lower emissions of ATR, due to easier CO_2 capture processes, are gaining attention for the achievement of environmental goals and this technology is considered in the early expansion state [7,13,71]. Membrane reforming, on the other hand, is attractive due to the integration of production and separation stages [65,66], while methane pyrolysis calls attention due to its zero-CO_2 production [64,67].

Indeed, as seen in Figure 1, SMR, ATR, and POX all produce syngas (CO + H_2) that passes through several H_2 clean-up stages. In addition to CO_2 removal, a CO elimination stage is necessary to be able to use the H_2 stream in fuel cells [72]. Although a single water–gas shift reaction (WGS) stage for CO removal could suffice for H_2 use in CO-tolerant fuel cells (which resist more than 5% CO [73]), these fuel cells are still an emerging technology. For commercial fuel cells, such as proton-exchange membrane fuel cells (PEMFC) that are not CO-tolerant (i.e., tolerate $\leq$ 50 ppm), a rigorous clean-up of the syngas is necessary [74], specifically, WGS followed by CO Preferential oxidation and/or Selective CO methanation [72]. Alternatively, Pressure Swing Adsorption (PSA) or Temperature Swing Adsorption (TSA) can also be used as a final step in syngas purification, achieving high purity (99.99% H_2), with high energy consumption (up to 8.89 W/kmol H_2) [75]. Meanwhile, H_2 produced through MP is commonly purified by treating the outlet stream with TSA and PSA [64,67], and MR directly produces high-purity H_2 suitable for PEMFC [65,66,69].

H_2 from other hydrocarbons can be obtained through Steam Reforming (SR) and ATR (light hydrocarbons, i.e., ethane, pentane, naphtha, and alcohols, i.e., methanol, ethanol) or POX (heavy hydrocarbons, i.e., heavy fuel oil or residual oil), followed by the clean-up stages described above [62,70,76]. However, the use of fossil fuels different from coal and NG for H_2 production is yet only attractive in places with low availability of these two fuels, or for the utilization of refinery residues [62,76]. On the other hand, the long-term decarbonization goals require a decline in the use of liquid fossil fuels, which could set the conditions for such fuels to become H_2 feedstock and continue to provide energy in a more sustainable way.

Finally, H_2 from coal is produced through gasification processes, with a variety of gasifier technologies available in the market [62,70]. Coal gasification produces syngas (CO + H_2) at variable compositions, which then follows the H_2 clean-up pathway that leads to high-purity H_2, as described above (Figure 1) [62,70,76]. More recently, underground coal gasification (UCG) has raised some interest and pilot projects are underway in Australia, China, and Canada; however, the environmental challenges of this alternative have restrained its deployment and it is still considered an emerging process [56,77]. Table 2 shows the carbon footprint of mature technologies for both gray and blue H_2 production.

Table 2. Carbon footprint of mature technologies for H_2 production from fossil fuels.

Type	Process	Carbon Footprint ($kg_{CO_2\text{-eq}}/kg_{H_2}$)
Gray	SMR	10.92 [4]
	ATR	11 [78]
	POX	10.7 [79]
	CG	24.2 [54,55]
Blue	SMR + CCS	2.7–5.8 [7,80]
	ATR + CCS	2.6 [7]
	CG + CCS	2.84 [81]

3.2. *Current State of Blue H_2 Deployment*

Currently, blue H_2 represents a minimal portion of global H_2 production, lower than 1% [5–8]. However, there is a renewed interest in its potential as a low-emission energy carrier, important in the energy transition, and thus it is included in the H_2 roadmaps of several countries, promoting its development in various regions worldwide. Table 3 shows blue H_2 production projects that are scheduled for the upcoming decades. Australia and Japan have endorsed a bilateral strategy for the development of pilot projects for H_2 production from coal, becoming one of the strongest international cooperation programs for the implementation of blue H_2 [17,82,83]. Depending on its results, this alliance is expected to foster the construction of blue H_2 facilities exceeding 180 kt/year, at a cost between 2.1 and 2.7 USD/kg_{H_2} [17]. Likewise, China began its commitment to H_2 from coal taking advantage of its position as the largest coal producer in the world (>3600 kt_{coal}/y) [84,85].

USA's H_2 roadmap [86] highlights that blue H_2 could be obtained from oil, NG, coal, plastic waste, or a mixture of them. Thus, the "21st Century power plants program"—led by the National Energy Technology Laboratory—aims to reduce the price of blue H_2 to below 2.1 USD/kg_{H_2} with a mixture of coal/NG/plastic waste [86]. However, most of the projects under development have focused on the use of NG to obtain H_2 (see Table 3). In Europe, England already has nine projects associated with blue H_2, Germany began in 2018 an ambitious program to be the largest producer of blue H_2 in Europe by 2027 [18,87], and Russia seeks to export more than 2 Mt_{H_2}/year by 2035 [88], most probably from NG and coal, given Russia's position as the second-largest producer of NG and fifth-largest producer of coal worldwide [84,88–90].

The development of blue H_2 in Latin America, on the other hand, is not clear yet: blue H_2 is mentioned in Brazil's H_2 roadmap [91], but neither what raw materials are to be used nor its contribution to the total H_2 production are described; the strategies of Chile [92], Costa Rica [93], and Peru [94] focus exclusively on green H_2; while Argentina [95] does consider H_2 from NG within its H_2 implementation policy (still under construction). This inconclusiveness on the future of blue H_2 in the region could provide an opportunity for Colombia to become a pioneer in the implementation of these production technologies and lead the development of blue H_2 in the region.

Table 3. Projects for blue H_2 production.

Project Name	Country	Estimated Capacity (kt_{H_2}/year)	Process	Organization/Facility	Intended Operation Year	Investment (b.USD)
Brown Coal-to-H_2 project	Australia and Japan	≤1 (pilot) >180 (expected)	CG + CCS	Japan's Electric Power Development Co (J-Power) and Australia's AGL Energy Ltd.	2021–2050	0.3 (pilot)
Sinopec Qilu Petrochemical CCS Project	China	3500	CG + CCS	China Petroleum & Chemical Corporation	2021–2025	Not reported
Low-carbon blue ammonia	United Arab Emirates (UAE)	Not reported	SMR + CCS	UAE's state oil company (ADNOC)	2022–2030	Not reported
Alberta Carbon Trunk Line	Canada	100	Asphaltene gasification + CCS	Sturgeon refinery	2017–2025	1.1
The North Dakota H_2 Hub	USA	310	ATR + CCS	Bakken Energy, LLC	2023–2027	2
Air Products' Blue H_2 Energy Complex	USA	650	SMR + CCS	Air Products	2021–2050	4.5
'Blue' H_2 project (H_2 Teesside)	UK	260 (1 GW)	SMR + CCS	BP plc and UK government	2027–2050	Not reported
The Humber Hub Blue Project	UK	185 (720 MW)	SMR + CCS	Shell and Uniper	2024–2027	Not reported
H_2-morrow project	Germany	≤1	SMR + CCS	Equinor and Open Grid Europe (OGE)	2018–2027	Not reported
Roadmap for H_2 production	Russia	≥5	SMR + CCS	Russian government	2021–2050	Not reported

Currently, H_2 in Colombia (ca. 140 kt/year) is produced from NG through SMR, 90% of it without CCUS [16]. The recently launched National Hydrogen Roadmap envisions 50 kt/year of blue H_2 by 2030, either by replacement or retrofitting of current gray H_2 processes, and it expects blue H_2 to be more cost-competitive than gray H_2 by 2035 [16]. In this context, Law 2099 of 2021 grants tax benefits to producers of green and blue H_2, aiming at a low-emission H_2 production of up to 120 kt/year by 2030 as well as satisfying a demand of 1850 kt/year by 2050, striving to make H_2 production pathways attractive for the fossil fuel industry [16]. The potential of each non-renewable resource available in Colombia to produce blue H_2 is reviewed below.

3.3. *Assessment of Fossil Fuel Reserves for H_2 Production in Colombia*

Oil, NG, and coal industries represent around 35% of Colombian exports, generating more than 70,000 direct jobs. While fossil fuels are available throughout the territory, the highest concentration of oil and NG reserves is in the Eastern Plains region, with Casanare and Meta representing 70% of oil reserves, and Casanare representing 59% of NG reserves [96]. The Caribbean region is the main source of coal in Colombia, where La Guajira and Cesar contribute 80.5% of the coal reserves [23,97]. Figure 2 shows the fossil fuel reserves distribution in the Colombian territory [23,96,97].

Proven NG reserves in Colombia (Figure 1) translate into ~8.2 years of self-sufficiency at the current annual consumption (1.09×10^{10} Nm^3, i.e., 385 Gscf) [44–46]. This indicates that large-scale blue H_2 production from NG in Colombia would be only temporary, unless reserves increase in the near future or gas imports are considered for H_2 production. Furthermore, H_2 from NG (e.g., for heating) may not be competitive compared to the direct use of NG.

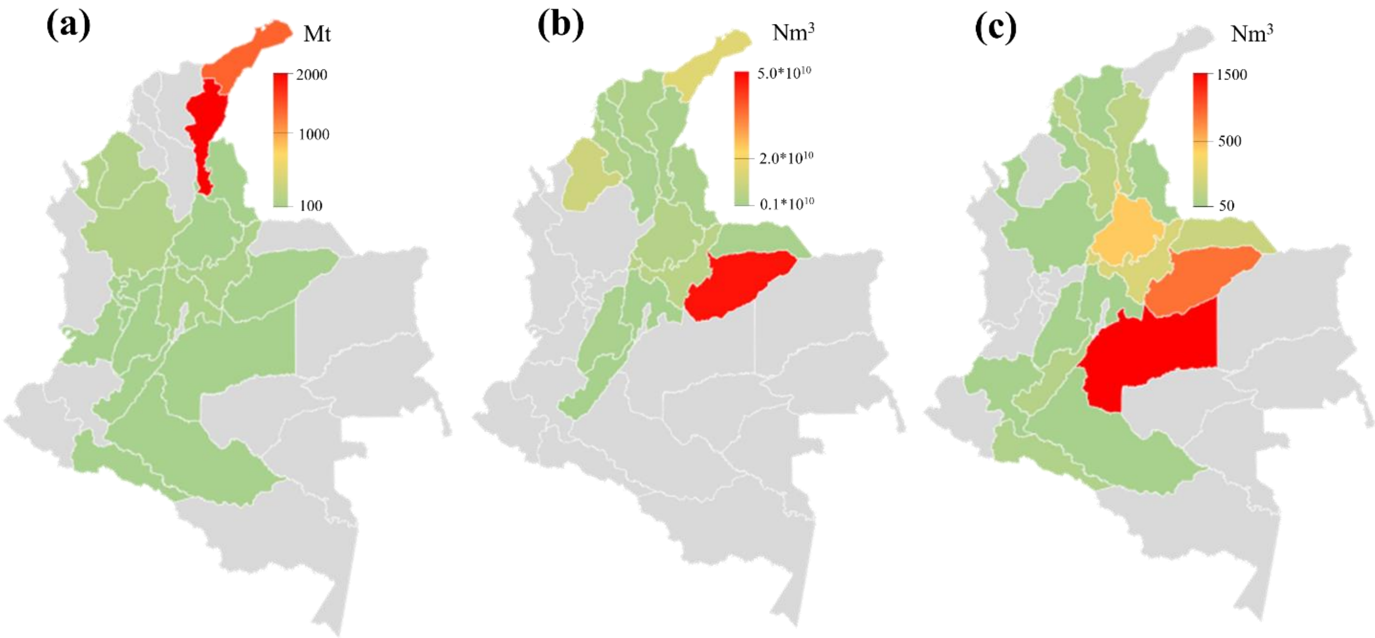

Figure 2. Colombia's proven reserves of (**a**) coal, (**b**) NG, and (**c**) oil.

Similarly, Colombian oil reserves (Figure 1) yield ~7.2 years of self-sufficiency at the current production rates (1.26 $\times$ 10^5 m^3/day) [44–46]. This short-term availability renders oil and its derivatives an unfeasible source for H_2 production unless—as in the case of NG—reserves increase significantly in the near future and this matches a major decrease in the direct use of fossil fuels. Such an increase in oil and NG reserves would require the implementation of fracking in several fields, which is a controversial technique and may not be allowed in Colombia in the near future.

On the other hand, Colombia is the lead coal producer in Latin America, ranking third in coke and fourth in thermal coal production worldwide [43]. Proven coal reserves in Colombia reached 4554 Mt in 2021 and estimated reserves were 16,569 Mt in 2019 [22,43]. At an annual production rate of 84.5 Mt [23], the country has coal for nearly 54 years from proven reserves and over 190 years considering the estimated ones. Most of this coal is exported, thus becoming the main mining export product and a major contributor to the country's economy [20,23]. However, both global warming and environmental agreements demand urgent decarbonization of energy systems and production processes [2,14,98], encompassing a decrease in global coal consumption that could significantly affect Colombian economy if more sustainable alternatives are not considered [20]. Blue H_2 production from coal could then provide an alternative for the mining sector to use such important reserves in a more sustainable way.

3.4. Blue H_2 from Coal in Colombia

3.4.1. Potential from Colombian Coal

Blue H_2 production potential from Colombian coal was estimated considering that the country's exports will behave in accordance with global coal demand projections under several scenarios (Table 1). Figure 3 shows the projected decrease in global coal demand under the compared scenarios. Only Equinor's Rivalry scenario projects coal demand above 2019 level, peaking in 2040, while all other scenarios project a monotonically decreasing demand. Conservative scenarios reach near 150 EJ in 2050, whereas moderate and ambitious scenarios reach 103–125 EJ and 12–36 EJ, respectively, corresponding to 6.5%, 22–35%, and 78–90% decreases from 2019 values, respectively; the latter required to reach Net-Zero emissions in 2050.

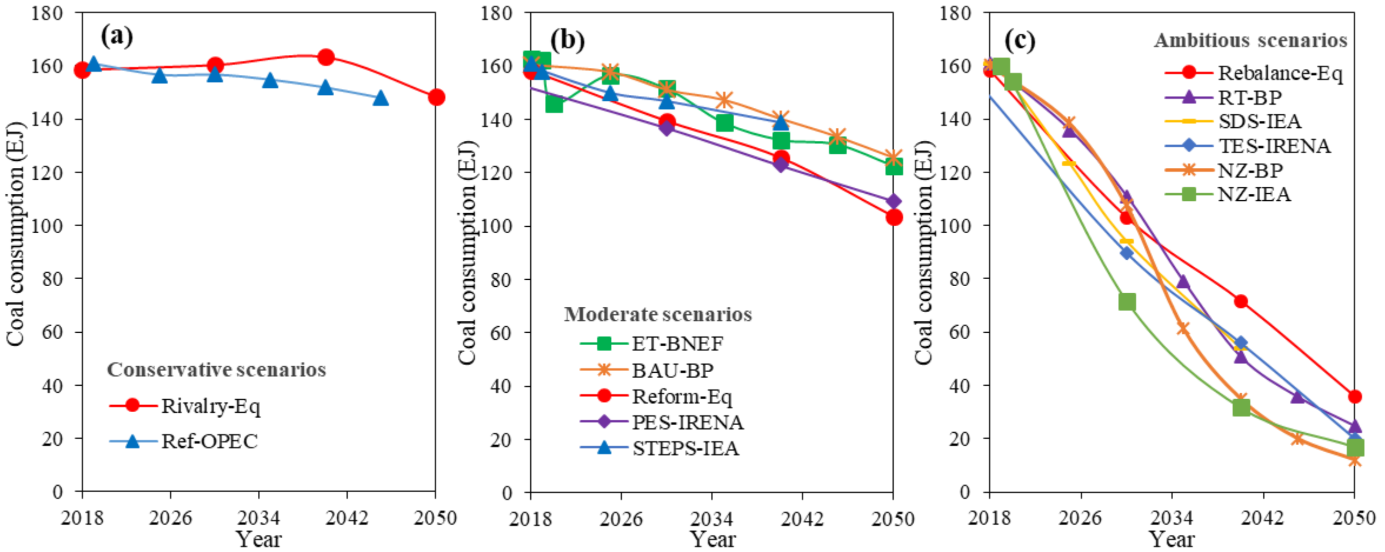

Figure 3. Global coal consumption (1 EJ = 1 × 10^{18} J) under (**a**) conservative, (**b**) moderate, and (**c**) ambitious scenarios, as described in Table 1.

The decline in coal consumption evidenced in all scenarios in Figure 3 indicates that enough coal would be available to be used as H_2 feedstock. As explained in Section 2, considering that Colombian coal exports decrease in the same proportion as global coal demand is projected by each scenario, the amount of H_2 that could be produced from such coal was obtained for each case. Figure 4 shows the potential blue H_2 production in Colombia if the coal not marketed due to the projected demand decreases were used as feedstock. Since Equinor's Rivalry scenario projects an increase in coal demand up to 2040, no coal would be available for H_2 production under this scenario, hence the negative H_2 values in Figure 4a; however, from 2045 there could be H_2 production from coal under this conservative scenario. All other scenarios would allow H_2 production from 2025 and 2030, the ambitious scenarios showing steeper increases as expected.

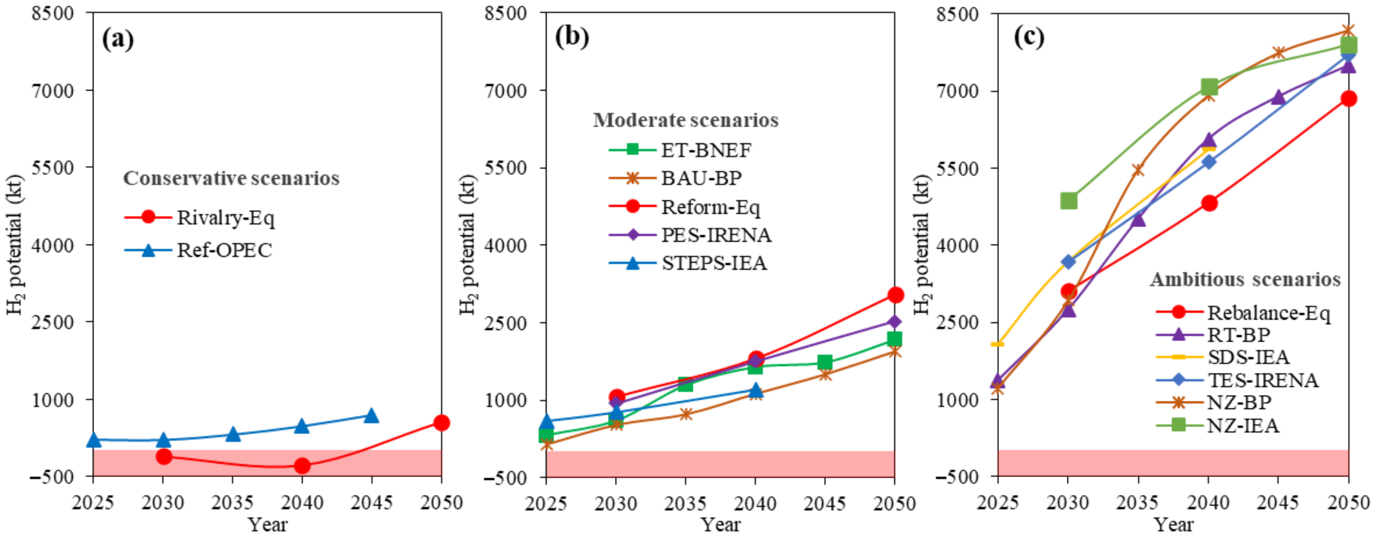

Figure 4. Potential H_2 production from coal in Colombia under (**a**) conservative, (**b**) moderate, and (**c**) ambitious scenarios, as described in Table 1. Shaded areas indicate negative values (no coal available for H_2 production).

Table 4 shows the ratios in 2030, 2040, and 2050 of the potential blue H_2 production in Colombia, as calculated under each studied scenario, to the low-emission H_2 demand in Colombia as projected in the National Hydrogen Roadmap [16]: 120 kt by 2030, 790 kt by 2040, and 1850 kt by 2050. Though conservative scenarios would not supply enough H_2 to meet the projected demand, blue H_2 from coal still constitutes a rather important contribution to supply internal demand under these scenarios. Meanwhile, both moderate and ambitious scenarios have the potential to meet and exceed Colombia's projected H_2 needs by 2050, resulting in a surplus that could be exported.

Table 4. Ratio of Colombian potential blue H_2 production to national low-emission H_2 demand as projected in the National Hydrogen Roadmap. Scenarios described in Table 1.

Type	Institution	Scenario	2030	2040	2050
Conservative	Equinor	Rivalry	−0.83	−0.34	0.31
	OPEC	Reference	1.87	0.62	n.a. *
Moderate	BP	BAU	4.37	1.42	1.05
	BNEF	ETS	5.07	2.09	1.18
	IEA	STEPS	6.45	1.53	n.a. *
	IRENA	PES	7.85	2.22	1.37
	Equinor	Reform	9.00	2.30	1.65
Ambitious	Equinor	Rebalance	25.86	6.11	3.71
	BP	RT	22.88	7.68	4.05
	IEA	SDS	30.67	7.43	n.a. *
	IRENA	TES	30.74	7.11	4.16
	IEA	NZ-IEA	40.59	8.97	4.28
	BP	NZ-BP	24.35	8.76	4.43

* n.a.: Data not available for this year and scenario.

Having compared the potential of Colombian blue H_2 production capacity to the projected national H_2 demand, it is now worth comparing it to the worldwide demand of H_2. Global H_2 demand has been projected to 240–800 Mt/year, depending on the scenario and energy outlook [12,15,50–52,58]. Considering the value reported by the International Energy Agency (530 Mt), an optimistic yet intermediate value, Table 5 shows the share (%) of such global demand that could be supplied with the blue H_2 produced from coal in Colombia, ranging from 0.11%, in a conservative scenario, to 1.55%, in a Net-Zero scenario. While this may seem low, current Colombian coal exports represent 5.5% of global coal trade and 1% of global coal consumption [20,84,99]. In addition, blue H_2 from coal would not be the only source of low-emission H_2 in Colombia, since the country also has significant potential for green H_2 production [16], which could increase the H_2 export capabilities and position H_2 as an important product for the Colombian economy.

3.4.2. Carbon Capture, Utilization, and/or Storage

CO_2 capture technologies are classified in four categories: absorption, adsorption, cryogenic separation, and membrane separation [78,100]. Among them, membrane separation is at an early development stage, while the others are technologically mature, with absorption being the most deployed [100]. According to their location in the process, they can be further classified as pre-combustion, post-combustion, and oxy-combustion processes [100]. For gasification, SMR, and ATR processes, pre-combustion CO_2 capture has been found to be the most economical, though the combination of both pre- and post-combustion capture is necessary to reach higher net capture efficiencies (96%) [78,100].

Even though these technologies are mature and widely used in other processes, the adoption of CCUS in H_2 production raises at least some concerns. Challenges in retrofitting, production upscaling and supply logistics, costs favoring large projects, and public acceptance (due to continued use of fossil fuels) are issues under consideration [13]. In addition, the development and deployment of CCUS has not yet matched the objectives set in the last decade (there have been significant delays and abandoned projects) [13].

Table 5. Share of global H_2 demand potentially supplied by Colombian blue H_2. Scenarios described in Table 1.

Type	Institution	Scenario	Share in 2050 (%)
Conservative	Equinor	Rivalry	0.11
	OPEC	Reference	n.a. *
Moderate	BP	BAU	0.37
	BNEF	ETS	0.41
	IEA	STEPS	n.a. *
	IRENA	PES	0.48
	Equinor	Reform	0.58
Ambitious	Equinor	Rebalance	1.30
	BP	RT	1.41
	IEA	SDS	n.a. *
	IRENA	TES	1.45
	IEA	NZ-IEA	1.49
	BP	NZ-BP	1.55

* n.a.: Data not available for this year and scenario.

Furthermore, blue H_2 production is not essentially CO_2-free. Though capture efficiencies can be as high as 85–95%, current industrial applications for H_2 production are in the range of 31–54% [7,13,70]. Large amounts of GHG emissions may result from obtaining and pre-processing the feedstock and can be released to the environment, depending on CO_2 application after capture (e.g., in enhanced oil recovery, EOR), so life-cycle emissions must be considered to evaluate the net effect of CCUS [13,70,80,101]. Even with these concerns on the table, the pressing need for decarbonization has led institutions, researchers, and policymakers to continue considering blue H_2 as a bridging solution towards green H_2 and a necessary step towards net-zero GHG emissions, hoping for a synergy between blue and green H_2 for their deployment [13,14,16–18,70].

CO_2 capture and storage capabilities could curtail the potential for blue H_2 production. Since H_2 production from coal is a carbon-intensive activity (Table 2), efficient carbon capture processes must be included for the production to be considered low-emission, and enough storage and/or utilization facilities must be available in the country. Thence, specific studies on Colombia's CO_2 storage potential are needed to fully comprehend its blue H_2 potential.

Figure 5 shows the amount of CO_2 to be captured and stored in Colombia under the studied scenarios, considering 22 kg_{CO_2} to be captured per kg_{H_2} produced, as mentioned in Section 2 [54]. Since this CO_2 should not return to the atmosphere, the country's capture capacity should account for the cumulative storage/utilization of this CO_2, and this could be a limiting factor for blue H_2 deployment.

CO_2 can be safely stored in geological formations, such as depleted oil and gas fields, coal seams, and deep saline reservoirs, or used as industrial feedstock and for enhanced oil recovery (EOR) [102]. Yáñez et al. have investigated the country's potential for CCUS through CO_2-EOR and found promising results (ca. 200 Mt CO_2) through a rapid screening method [103,104], while Mariño and Moreno reported that the Casanare region would be appropriate for geological storage [105]. Given the Colombian role as a fossil fuel producer, further potential could be found in the depleted oil and gas fields and the exploited coal seams, which cover a sizable part of the national territory, as shown in Figure 2. On the other hand, utilization of CO_2 captured in blue H_2 production or in other industrial processes does not appear feasible in the short term. In fact, there is availability of high-purity CO_2 from bioethanol production (ca. 250 kt_{CO_2}/y), which can be used directly in the food industry. In addition, the cement industry—another potential large consumer of CO_2—is focused on reusing its own emissions (ca. 4.5 Mt_{CO_2}/y) [106]. An accurate appraisal of Colombia's CO_2 capture capacity is thus essential for the estimation of Colombian blue H_2 production potential. Furthermore, the relative locations of sources and sinks should be considered to get a better assessment of capture costs, as suggested by Yáñez et al. [103,104].

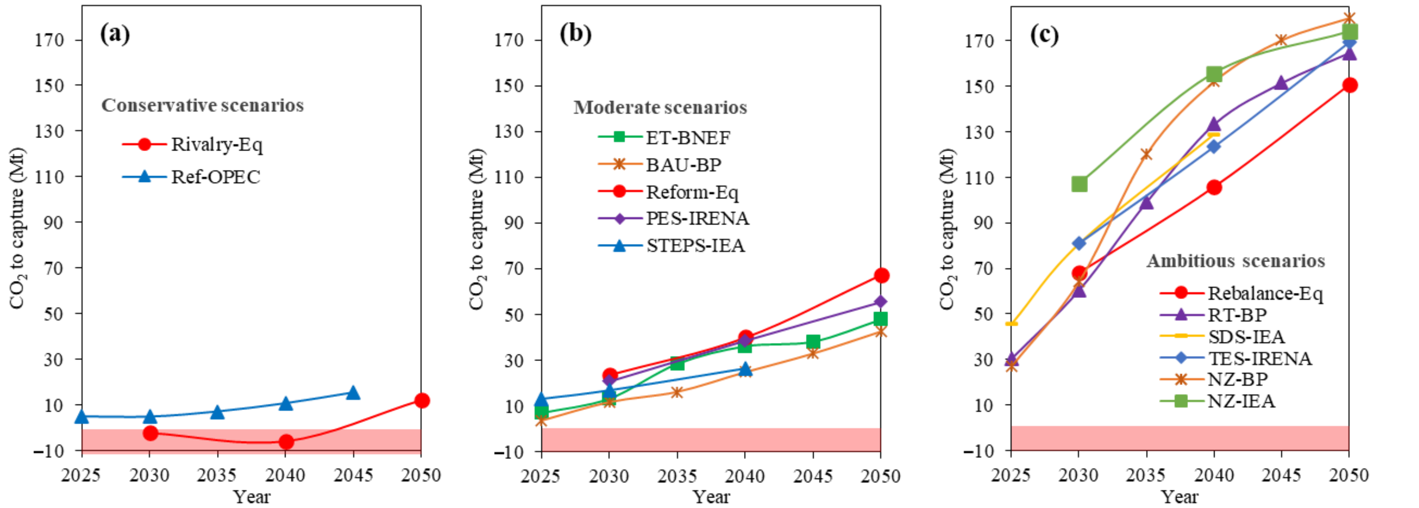

Figure 5. CO_2 to be captured in Colombia from blue H_2 production from coal under (**a**) conservative, (**b**) moderate, and (**c**) ambitious scenarios, as described in Table 1.

3.4.3. Assessment of Investment Costs

As important as technical aspects, economic constraints are a decisive factor. For three of the studied scenarios, investment costs were obtained, as explained in Section 2. Table 6 shows the number of large-scale plants (i.e., 1667 MW, equivalent to 438 kt_{H_2}/year) required to meet the demand in the reported years and the investment costs involved.

Table 6. Investment cost estimation for blue H_2 production from coal in Colombia under selected scenarios. Scenarios described in Table 1.

Type	Scenario		2030	2035	2040	2045	2050
Conservative	Reference-OPEC	# Required Plants	1		2		
		Cumulative Investment cost (M. USD_{2010})	805.37		1610.73		
Moderate	BAU-BP	# Required Plants	2		3	4	5
		Cumulative Investment cost (M. USD_{2010})	1610.73		2416.10	3221.46	4026.83
Ambitious	Net Zero-BP	# Required Plants	7	13	16	18	19
		Cumulative Investment cost (M. USD_{2010})	5637.56	10,469.75	12,885.84	14,496.57	15,301.94

Colombia's National Hydrogen Roadmap envisions USD 2500 to 5500 M. public + private investment to achieve the stated goals by 2030, which includes both green and blue H_2 deployment, research and education activities, and governance measures [16]. Thence, both the conservative and moderate scenarios would be within Colombia's expected investment by 2030. Even with no further ventures, the conservative scenario could be attained. The moderate scenario could be attained in the case of the USD 5500 M. investment scenario, but would require most of the resources to be directed to coal gasification, which may not be consistent with the stated primary interest in green H_2. The ambitious scenario, on the other hand, exceeds the highest expected investment even in 2030, highlighting the need to update (and possibly modify) the assumptions used in the Hydrogen Roadmap if such scenarios were to be pursued.

Low investment in research and development (R&D) in science, technology, engineering, and math (STEM) has limited industrialization in Colombia, requiring new technologies to be imported, mainly from the USA, Europe, and China [107]. The import process is expensive, which affects the establishment of new processes, such as blue H_2 production. According to Colombian policies, technologic imports have an extra customs tariff of 10% [108], and when the value of the imported goods exceeds USD 1000, a customs agent must be hired, with a cost of 0.18% to 0.48% of the total value of the equipment. In addition, the costs of packaging, documentation, insurances, international freight, storage in seaports, currency exchange, and bank fees could double or triple the importing costs. These factors increase the costs estimated in Table 6, limiting the potential to produce blue H_2 from coal in Colombia. Thus, although Law 2099 grants an exemption of the Value Added Tax (VAT) for the development of non-conventional energy source projects [109], the success in the production of low-emission H_2 and the achievement of the goals proposed in the National Hydrogen Roadmap will depend on the mechanisms adopted by the government to promote the development of local technology and/or grant further tax benefits to importers of blue H_2 technology, as is currently conducted with emerging technologies such as electric vehicles [110].

4. Conclusions

Energy transition to achieve decarbonization has positioned H_2 in the spotlight as a low-emission energy carrier. Colombia, a growing economy with a great dependence on fossil resources, needs to find alternatives to use them in a sustainable way, and thus blue H_2 appears as an option to move towards a decarbonized economy. While blue H_2 production from oil is yet unfeasible, and from NG seems to be a temporary option and limited to the refinery sector, the abundance of coal makes it an attractive resource for H_2 production in the country. Results of this work indicate that H_2 produced from not-marketed coal could cover and exceed the projected national demand (i.e., 1850 kt H_2 by 2050); namely, the surplus could be exported and thus replace coal's current role to some extent.

Introduction of blue H_2 to the energy matrix could promote H_2 use in the short to medium term and open the road to extended green H_2 uses. However, Colombia must ensure an investment of at least USD 1610 M. (conservative scenario) to position blue H_2. Investment is increased by the absence of local technologies for converting coal to low-emission H_2, including CCUS technologies, which creates a need for policies that facilitate technology imports and/or initiatives that rapidly promote local research on blue H_2 technologies.

While feedstock availability paints a promising picture for blue H_2 production, investment costs and CO_2 capture capacities could limit this potential in Colombia. Further studies on CCUS capacity, the development of a clear public policy, and a more detailed roadmap for the inclusion of blue H_2 in the energy matrix are required steps for the establishment of H_2 in the country.

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Abbreviations

ADNOC	Abu Dhabi National Oil Company
ANH	Agencia Nacional de Hidrocarburos
ANM	Agencia Nacional de Minería
ATR	Autothermal Reforming
b.USD	billion United States Dollars
BAU	Business-as-Usual
BNEF	Bloomberg New Energy Finance
BP	British Petroleum Co.
CCS	Carbon capture and storage
CCUS	Carbon Capture Utilization and/or Storage
CG	Coal Gasification
CO	Carbon monoxide
CO_2-eq	CO_2 equivalent
CO-PROX	Preferential oxidation of CO
CO-SMET	Selective CO methanation
COVID-19	Coronavirus Disease 19 Pandemic
EOR	Enhanced Oil Recovery
ETS	Economic Transition Scenario
GHG	Green House Gases
Gscf	Giga standard cubic feet
IEA	International Energy Agency
Inv.	Investment
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
LS	Large-scale
M.EUR2010	Million euros of 2010
M.USD	Million USD
MP	Methane Pyrolysis
MR	Membrane Reforming
MS	Medium-scale
n.a.	Data not available for this year and scenario
NDC	National Determined Contribution
NG	Natural Gas
NZ	Net-Zero emissions
OPEC	Organization of Petroleum Exporting Companies
PEN 2020–2050	Plan Energético Nacional (National Energy Plan) 2020–2050
POX	Partial Oxidation
PSA	Pressure Swing Adsorption
R&D	Research and Development
Ref.	Reference
RT	Rapid Transition
SDG	Sustainable Development Goals
SDS	Sustainable Development Scenario
SMR	Steam Methane Reforming
SR	Steam Reforming
STEM	Science, Technology, Engineering, and Math
STEPS	Stated Policies Scenario
TES	Transforming Energy Scenario
TSA	Temperature Swing Adsorption
UAE	United Arab Emirates
UCG	Underground Coal Gasification

UK	United Kingdom
UN	United Nations
UPME	Unidad de Planeación Minero-Energética
VAT	Value Added Tax

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