energies

Article

Renewable Energy Sources for Green Hydrogen Generation in Colombia and Applicable Case of Studies

Juan José Patiño [1], Carlos Velásquez [1], Edwin Ramirez [1], Rafael Betancur [1], Juan Felipe Montoya [1], Edwin Chica [1], Pablo Romero-Gómez [2], Arunachala Mada Kannan [3], Daniel Ramírez [1], Pedro Eusse [4] and Franklin Jaramillo [1,*]

1 Centro de Investigación, Innovación y Desarrollo de Materiales—CIDEMAT, Universidad de Antioquia (UdeA), Calle 70 No. 52-21, Medellín 050010, Colombia; carlos.velasquez2@udea.edu.co (C.V.); ramirezp.edwin@gmail.com (E.R.); randres.betancur@udea.edu.co (R.B.); felipe.montoya@udea.edu.co (J.F.M.); edwin.chica@udea.edu.co (E.C.); estiben.ramirez@udea.edu.co (D.R.)
2 Department of Applied Physics I, University of Málaga, 29071 Málaga, Spain; prg@uma.es
3 The Polytechnic School, Ira A. Fulton Schools of Engineering, Arizona State University, Mesa, AZ 85212, USA; amk@asu.edu
4 Empresas Públicas de Medellín (EPM), Medellín 050012, Colombia; pedro.eusse@epm.com.co
* Correspondence: franklin.jaramillo@udea.edu.co

Abstract: Electrification using renewable energy sources represents a clear path toward solving the current global energy crisis. In Colombia, this challenge also involves the diversification of the electrical energy sources to overcome the historical dependence on hydropower. In this context, green hydrogen represents a key energy carrier enabling the storage of renewable energy as well as directly powering industrial and transportation sectors. This work explores the realistic potential of the main renewable energy sources, including solar photovoltaics (8172 GW), hydropower (56 GW), wind (68 GW), and biomass (14 GW). In addition, a case study from abroad is presented, demonstrating the feasibility of using each type of renewable energy to generate green hydrogen in the country. At the end, an analysis of the most likely regions in the country and paths to deploy green hydrogen projects are presented, favoring hydropower in the short term and solar in the long run. By 2050, this energy potential will enable reaching a levelized cost of hydrogen (LCOH) of 1.7, 1.5, 3.1 and 1.4 USD/kg-H_2 for solar photovoltaic, wind, hydropower and biomass, respectively.

Keywords: green hydrogen generation; renewable energy potential; LCOH; hydropower; solar; wind; biomass

check for updates

Citation: Patiño, J.J.; Velásquez, C.; Ramirez, E.; Betancur, R.; Montoya, J.F.; Chica, E.; Romero-Gómez, P.; Kannan, A.M.; Ramírez, D.; Eusse, P.; et al. Renewable Energy Sources for Green Hydrogen Generation in Colombia and Applicable Case of Studies. *Energies* **2023**, *16*, 7809. https://doi.org/10.3390/en16237809

Academic Editor: Vladislav A. Sadykov

Received: 25 July 2023
Revised: 10 August 2023
Accepted: 18 August 2023
Published: 27 November 2023

1. Introduction

The current energy supply in Colombia exemplifies the global need for an energy transition toward low-carbon energy sources. According to the Unidad de Planeación Minero Energética (UPME), the total energy demand in Colombia in 2020 was mainly based on liquid fuels, natural gas and electricity, as shown in Table 1 [1]. Concretely, the energy transition needs to address simultaneously the reduction in polluting gases and supplying the increasing energy demand expected in the coming years. The current strategy to solve both challenges is through electrification using clean renewable energy sources. The geographical location of Colombia allows the development of several clean energy sources including wind, hydropower, and solar energy. Historically, hydropower has been successfully exploited to the point that the country is recognized as having one of the cleanest electricity grids in the world [2]. However, there is an electricity supply risk due to the excessive dependence on hydropower, which is strongly affected by weather conditions as has already happened in the past [3].

Table 1. Energy demand in 2020 in Colombia and projection to 2036 for the main current energy sources.

Sources	Demand in 2020	Average Growth Rate per Year during 2022–2036 (%)
Liquid fuels (GWh-eq)	165	1.3
Natural gas (GWh-eq)	93	0.5
Electricity (GWh)	76	2.5

In this direction, diversification of the energy sources favors energy production and enables reaching nationwide energy coverage taking advantage of the diverse ecosystems and environments. The diversification challenge is also required, since it is impossible to think of constant renewable energy generation due to the variability of climatic conditions such as the solar brightness, droughts and intermittent wind currents that prevent the constant generation of electricity. In this context, there is an evident need to implement energy storage solutions to secure renewable energy generation. The most widespread solution is being provided by batteries, which have disadvantages with respect to hydrogen due to their heavy weight, long charging time and larger carbon footprint in their lifespan. In contrast, hydrogen can be used as a storage source and as an energy carrier for multiple applications and industries, as shown in Figure 1. Additionally, hydrogen has a higher calorific value than other fuels used industrially.

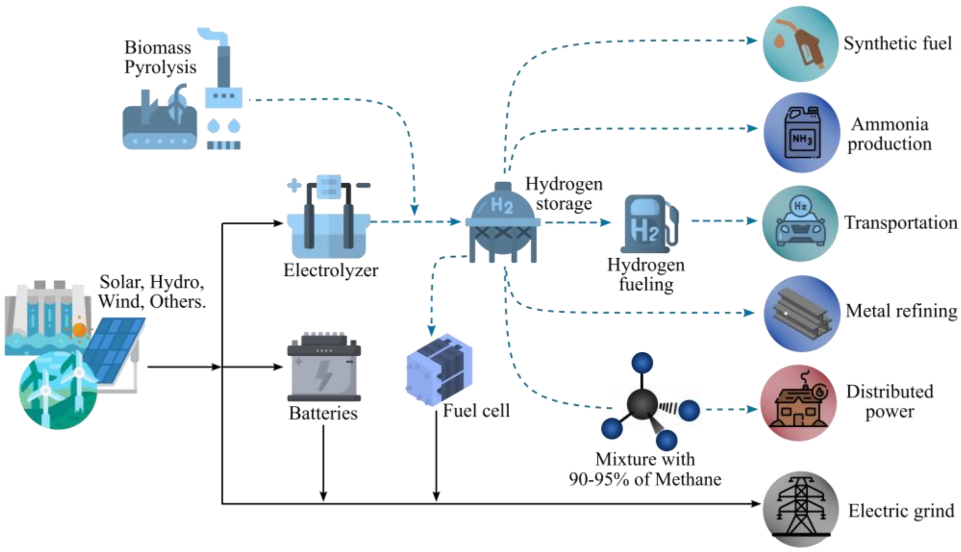


Figure 1. Hydrogen chain from the sources and production processes to final applications. Own scheme, inspired from [4], icons from Flaticon.Com.

Hydrogen represents an energy carrier like electricity in the sense that it can be produced from different sources and used in various applications [5]. The diversity of the sources and processes to generate hydrogen has led to a color classification where each color has a different carbon intensity ([$KgCO_2/KWh$] = $KgCO_{2eq}$), as shown in Table 2. For the particular case of green hydrogen, the most spread definitions state it as [6–8]:

- "The hydrogen produced by splitting water into hydrogen and oxygen using renewable electricity";
- "Green hydrogen projects operate with less than 4.37 kg CO_{2eq} per kg H_2".

Table 2. Hydrogen color classification [6,7].

Terminology of Hydrogen	Source	Process	Carbon Intensity ($kgCO_2$-eq/kgH_2)
Green	Renewable	Water electrolysis	<4.37
Blue	Coal and Natural Gas + CCUS *	Natural gas refurbishment + CCUS *	<4.37
Turquoise	Biogas	Pyrolysis	Solid Carbon (by-product)
Grey	Natural Gas	Natural gas refurbishment	11.3–12.1
Brown	Lignite	Gasification	>19
Black	Coal		

* CCUS: Carbon Capture, Use and Storage.

Reaching a viable production of green hydrogen requires low-cost renewable energy sources. To quantify this, the levelized cost of energy (LCOE) indicator is used to compare energy sources based on the price per MWh produced over their lifetime. In the last decade, the LCOE of renewable energy has become competitive when compared to hydrocarbon-based sources. That is the case of solar photovoltaic energy, which has reduced by 87% during this period of time. Similarly, onshore and offshore wind energy have reduced their LCOE values by 64% and 57%, respectively [9]. This scenario favors the generation of renewable energy reaching a competitive levelized cost of hydrogen (LCOH), which represents the cost per kg of H_2 generated over the lifetime of the technology employed. In 2016, the LCOH of hydrogen produced from solar energy and PEM electrolysis was 13 USD/Kg-H_2 [10]. Fortunately, this cost has decreased to 5–6 USD/kg-H_2 [11] thanks to the economy of scale [12]. This perspective makes hydrogen produced from renewable sources attractive in the long term. In fact, by 2030, it is expected to reach values below 2 USD/kg-H_2 [11]. An interesting case can be found using biomass pyrolysis, which potentially can lead to an LCOH between 2.8 and 3.4 USD/kg-H_2 [10]. This LCOH is above the one achieved by fossil fuels (1.5–2.4 USD/kg-H_2) but below that produced by solar, hydro and wind energy. According to the World Bank, 2000 million tons of urban solid waste is generated each year [13], which can produce 100 million tons of hydrogen per year with a yield of 0.05 kg-H_2/kg-waste [10]. This raises a good prospect for the use of biomass pyrolysis as a renewable source along with those mentioned above. However, biomass pyrolysis has disadvantages, which are its future availability if used on a large scale and the need to use gas heating and handle residual carbon capture during the production process. Finally, it is worth mentioning that besides the LCOH, it is required to consider the carbon intensity (Table 2) to assess the sustainability level of each energy alternative.

The aim of this work is to identify the most prominent renewable energy sources in Colombia attending its natural resource potential and the application of each renewable energy source to generate hydrogen. The last is exemplified using a case study developed in other countries including its production, efficiency and costs. Finally, the deployment of similar projects in the country is analyzed from the perspective of the generation.

2. Solar Power for Green H_2 Generation

Solar energy is the most abundant renewable energy resource available. According to estimates, the world's energy demand could be met by installing 1% efficient solar panels in 1% of the global area of sun incidence [14]. In this regard, the geographical location of Colombia close to the equatorial region has considerable advantages for the implementation of photovoltaic systems. As can be seen in Figure 2a, the average solar radiation is around 4.5 kWh/m^2 per day with values close to 6.0 kWh/m^2 per day on the north coast of the country and in the region of Santander [15,16]. The radiation potential in Colombia has low variability during the year and is above most regions of the USA, Canada, and European countries, which makes it a promising country for the development of photovoltaic projects.

The adoption of solar technology in the country has been steadily increasing. In 2019, the total installed generation capacity reached 90 MW, which is equivalent to around 0.5% of the capacity of the national electrical grid [17], and it is expected to reach 741 MW in

2022 after including solar parks such as El Paso (Cesar, 86.2 MW) and San Fernando (Meta, 61 MW). The implementation of tax exemption policies, a regulatory framework for the sale of surplus electricity [18] and the design of renewable energy auctions have strongly fomented the implementation of solar technology which is evidenced by the addition of 1300 MW of new solar installations to be developed before 2025 [19]. This result is perfectly aligned with the plans of the government toward the energy transition and carbon neutrality goal by 2050 [20,21].

The most studied routes to generate hydrogen from solar energy using water splitting are solar thermochemical, photoelectrochemical, photovoltaic–electrochemical, and photocatalytic technologies. In addition, other novel routes include technologies based on photothermal catalytic and photobiological effects that are still at the research stage [22–26]. One of the most extensively reported routes is the photovoltaic−electrochemical water splitting in which two separate systems are employed: a photovoltaic cell and an electrolyzer. Both technologies are technically mature, economically competitive and have already been commercialized, reaching efficiencies levels around 18–22% and 60–83%, respectively. The combination of these facts is the main advantage of this route of hydrogen production despite its high energy requirements compared to other routes [22,27–29]. It is important to note that the photovoltaic–electrochemical route for H_2 production is the most energy-intensive and kinetically slow step in the overall water-splitting process [30].

2.1. Solar Potential in Colombia

Estimating the total solar potential of the country involves many assumptions that may be unrealistic. For instance, a study estimated that 12.3 TWh/year could be generated in the Caribbean region under the assumption of a constant amount of solar radiation throughout the year and using the entire area of the region [31]. In a more insightful way, a recent study [32] was conducted to estimate the total area available for solar energy projects (Figure 2b) considering characteristics and restrictions of the Colombian territory such as:

- Physical: wetlands, slopes, available area, etc.
- Biotic: protected areas, ecosystems, etc.
- Economic: distance to roads, electricity grid and urban areas, etc.
- Cultural: archaeological zones and ethnic territories.
- Political: post-conflict zones.

At the end, when considering the remaining available area, a solar power density of 0.5 MW/ha, and solar modules with 20% efficiency, it was determined that Colombia could generate 11,569 TWh/year with an installed power capacity of 8172 GW [32].

(**a**) (**b**)

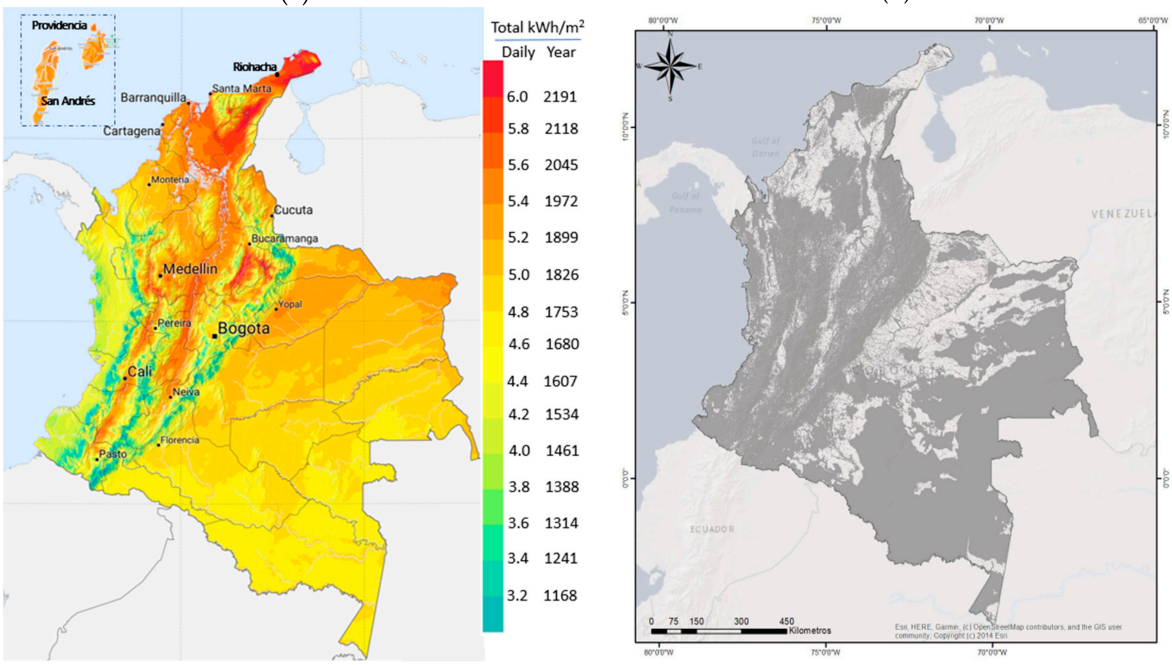


Figure 2. (**a**) Global horizontal irradiation. Total per day and per year (units: kWh/m^2). Adapted from Global Solar Atlas [15] which was published under Creative Commons CC BY 4.0, (**b**) Areas with some restrictions for solar projects (dark gray) [32]. Figure 2b was taken from "Análisis espacial multicriterio para la ubicación de parques eólicos y granjas solares en Colombia" [32], which was published under Creative Commons CC BY-ND 4.0.

Cities constitute an ideal environment to generate solar power. In general, population centers consume about 70% of the energy and in contrast have a low contribution to energy generation. In a study of the business opportunity of distributed solar generation (DSG) in Colombia [33], the technical potential of these installations was determined based on the meteorological conditions of the main Colombian cities (temperature and solar irradiation), the number of users and their monthly and annual electricity consumption, the housing conditions for the installation of a DSG system, and the restrictions on the use of the available physical space. It was found that about 8 million installations totaling 12.44 GW could be realized in the national residential sector [33]. Table 3 shows the solar radiation potential of the five most populated cities in the country [34]. From these values, the annual generation potential with a small residential system (installed capacity of 1 kWp) was estimated. Remarkably, thanks to the geographic location of Colombia, the photovoltaic electricity generation could be comparable or even higher than that generated by a solar plant of the same size located in cities where solar hydrogen generation systems are currently operating. For example, a solar plant located in Barranquilla would generate 330 kWh/m^2 per year more than a solar plant in Castres (France) where a solar generation station currently operates for self-consumption for mobility with a capacity of 74 Ton H_2/year [35]. These values show the great potential of Colombia to use decentralized photovoltaic systems for contributing to the energy diversification.

Table 3. Solar radiation potential in the most populated cities in Colombia and in cities currently operating solar H_2 generation projects around the world.

City	Global Tilted Irradiation (kWh/m^2/year)	PV Power Output—Small Residential (MWh/Year)	H_2 Application and Solar H_2 Production
Bogota	1741	1.36	NA
Medellín	2009	1.53	NA
Cali	2004	1.55	NA
Barranquilla	2126	1.61	NA
Cartagena	2085	1.58	NA
Worldwide cities with H_2—Solar projects in operation			
Castres (France)	1612	1.28	Mobility, 74 TonH_2/year [35]
Colina (Chile)	2270	1.72	Mobility, 0.7 TonH_2/year [36]
Shanghai (China)	1774	1.41	Mobility, 19 TonH_2/year [37]

2.2. Case Study: Solar for Green H_2 Generation

Spain has set the goal of achieving 4 GW electrolyzer capacity by 2030. Toward this end, Iberdrola and Fertiberia have developed the largest green hydrogen plant in Europe [38]. It involves a solar plus storage system unique in its kind. The location of the project was selected because of the availability of the solar resource and the direct use of green hydrogen to produce ammonia. The project constitutes a reference for a more ambitious plan of the companies to develop 830 MW capacity in electrolyzers before 2027 (Table 4).

Table 4. Case study: Solar for green H_2 generation (image source: Imagery © 2023 CNES/Airbus, Maxar Technologies, Map data © 2023 Inst. Geogr. Nacional).

Case Study Solar PV for Green H_2 Generation	
Project name	Iberdrola green hydrogen plant in Puertollano
Renewable energy source	Solar energy
Location	Puertollano, Castilla la Mancha, Spain
Solar potential in the region	Between 4.6 and 5 kWh/m^2
Developer	Iberdrola, S. A. and Fertiberia
Location selection criteria	A prime location with an important industrial hub and high solar irradiation in the zone
Hydrolysis technology	20 MW proton exchange membrane electrolyzer
Installed capacity	100 MW including a battery storage of 20 MWh/5 MW
Hydrogen production capacity	3000 ton-H_2/year
Project cost	EUR 150 million
Deploy time	Completed in May 2022
Status	Operational
Hydrogen end-use	Green fertilizers
References	[39–41]

The solar energy harvested in the case study in Puertollano could potentially be matched in most of the Colombian Caribbean cities and in country-side cities such as Tunja, La Pintada, Giron, Lebrija and Yopal, which are also close to agro-industrial centers requiring green fertilizers. However, in order to take advantage of Colombia's potential for solar photovoltaic generation, some challenges associated with the implementation of solar energy projects in Colombia are identified:

- Encouraging financial support and initial investment: The establishment of solar parks requires substantial initial investment and financing that can be leveraged with foreign or mixed public–private investment.
- Land use: Although Colombia has regions of high solar radiation potential, the regulation and facilitation of land use for solar PV projects limits their implementation due to protected areas and regions with restricted access due to violence.
- Boosting research and technological development: Research and technological development is essential to reduce Colombia's dependence on foreign countries for the production of solar panels, inverters, regulators and other critical components needed for PV installations.
- Expanding the grid: An imperative challenge is to expand the grid to accommodate the integration of solar energy and ensure its effective distribution.

3. Hydropower for Green H_2 Generation

Hydropower is the oldest form of renewable electricity. In terms of installed capacity, the top five countries are China (391 GW), Brazil (109 GW), the United States (102 GW), Canada (82 GW) and Russia (56 GW). Colombia is in the 20th place with 11.9 GW [42]. As agreed in COP26, to keep the global temperature rise below 1.5 °C and reach net zero emissions by 2050, the world leaders agreed to phase down coal. Hydropower has the potential to replace coal, since it provides both power and energy storage. However, this goal would require adding 45 GW/year of new hydropower capacity, and in the last 5 years, just an average of 22 GW/year has been added [43]. Remarkably, hydropower plants are the most challenging renewable energy projects. In general, they involve the following challenges:

- Environmental: affectation of forest and wildlife habitat.
- Social: human forced displacement, arbitrary decision on water usage and loss of patrimonial lands.
- Economic: loss of agriculture lands and high start-up costs.

Hydropower has an undeniable potential to generate hydrogen. In 2021, the global hydropower installed capacity reached 1.36 TW and generated 4.252 TWh [43], resulting in a relatively low 35.7% capacity factor (around the world, the capacity factor of hydropower projects lies in the range 25–80% [44]). If the current hydropower infrastructure were used up to a 75% utilization rate, the excess electricity would be able to generate all the current global hydrogen demand (94 million tons [45] assuming a 50 kWh/kg-H_2 during electrolysis). Interestingly, the use of hydropower to generate hydrogen was first implemented in 1927 when Norsk Hydro developed a 167 MW electrolyzer plant to supply H_2 for ammonia production at Rjukan, Norway [46]. In this section, the potential of hydropower in Colombia is presented as well as a case of study located in Québec, Canada.

3.1. Hydropower Potential in Colombia

Colombia is a country rich in water resources. In 2020, the installed hydropower capacity was 11.93 GW [47] and generated 68% of the electrical energy demand of the country (93% of this capacity is installed in large hydropower plants). In the same year, the final energy produced by all hydropower plants reached 47.28 TWh [47]. Accordingly, the hydropower facilities have a utilization rate of 45%. Clearly, the hydropower capacity is underutilized due to several factors including low electrical demand, strategic water management, and water lost through the spillways (512 GWh in 2020 [47]). Excess hydroelectricity has the potential to be used to generate hydrogen toward supporting the energy transition in the country.

A general analysis in the country estimated the potential of hydropower generation as 56 GW [48], which is characterized by hydropower plant type and hydrological region in Table 5 and Figure 3. This potential is mainly associated with large power plants (76.76%, plants > 40 MW) located across all the country but with less potential capacity in the Pacific and Caribbean regions.

Table 5. Hydropower potential in Colombia per type of power plant and region (units: MW) [48].

Region	Hydropower Plant Type						Percentage per Region
Hydropower Type Region	Pico	Micro	Mini	Small	Large		
					20–40 MW	>40 MW	
Amazonas	0.29	2.80	26.95	903.31	1518.30	9522.54	21.3%
Caribe	0.21	1.94	16.84	436.48	749.31	2922.07	7.3%
Magdalena-Cauca	0.51	5.23	47.57	1.646.20	2808.65	17,713.62	39.5%
Orinoco	0.36	3.60	35.79	1.230.96	2205.01	10,227.24	24.4%
Pacífico	0.17	1.65	15.98	568.66	831.95	2743.60	7.4%
Percentage per type	0.003%	0.03%	0.26%	8.52%	14.44%	76.76%	
TOTAL POTENTIAL				56.19 GW			100%

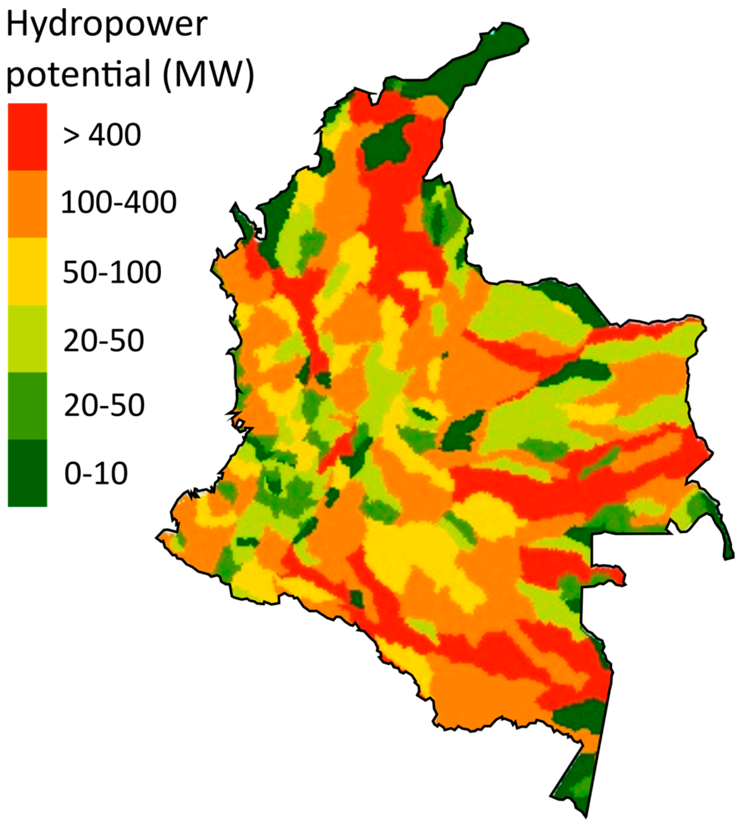


Figure 3. Hydropower potential in Colombia for a 1 km horizontal conduction length (units: MW). Sources: Esri, USGS | Esri, HERE, Garmin, FAO, NOAA, USGS [49].

The production of hydrogen from hydroelectricity is currently the most cost-effective in comparison with the rest of the renewables. Such economic competitiveness could be further increased if the H_2 production is based on the use of the surplus electricity due to demand reduction or increased production from the increase in water flows during the wet season in the power plants [50,51]. Perhaps the large-scale hydrogen market in Colombia through hydroelectricity could also be supported by the short-term market or energy market, which consists of a daily auction in which each generator offers a single price and its hourly availability for 24 h the next day. The price depends on each generator and is generally considered the opportunity cost of water. Currently, generators with more than 20 MW are required to enter the energy market; between 10 and 20 MW is optional and less than 10 MW is not centrally dispatched. After the price is agreed, all the generators are remunerated at the market price. This scheme to date has worked to cover the demand for energy in Colombia. In this sense, hydrogen generation plants could be created near the main export ports of the country and the large consumption centers supported by a short-term energy market destined to meet the energy demand of the electrolyzers from the daily surpluses of the country's generating companies.

3.2. Case Study: Hydropower for Green H_2 Generation

According to the IEA global Hydrogen Projects Database [52], there are two projects to generate green hydrogen from hydropower: one in final investment decision (FID) and the second one operational. Both projects are located in Canada. The operational project in Bécancour was selected as a case study as follows (Table 6).

Table 6. Case study: hydropower for green H_2 generation (image source: Imagery©2023 Airbus, CNES/Airbus, Maxar Technologies, Map data©2023).

Case Study Hydropower for Green H_2 Generation		
Project name	Air Liquide Bécancour	
Renewable energy source	Hydropower dedicated from Hydro-Quebec	
Location	Bécancour, Québec, Canada.	
Hydropower potential in the region	160.000 MW/Installed: 76.000 MW	
Developer	Liquid Air: a French multinational that provides industrial gases.	
Location selection criteria	The selection of the location was justified by the abundant clean energy from Hydro-Québec and access to the mobility market in the northeast of the continent	
Hydrolysis technology	Proton exchange membrane—PEM. HyLYZER® Water electrolyzers from Cummins	
Installed capacity	20 MW	
Hydrogen production capacity	3000 ton-H_2/year	
Project cost	Not available	
Deploy time	Under two years. Construction included the company Hatch	
Status	Operational	
Hydrogen end-use	Mobility and industry	
Cost of hydrogen	Not available but presumably 5–6 USD/kg-H_2 [53] USD$3.41 USD/kg-$H_2$ assessed by S&PGlobal using PEM in Alberta Canada [54]	
References	[55–58]	

As shown previously, the installed capacity of the Bécancour project is 20 MW, which could be easily reached by any large hydropower plant in Colombia. However, clearly, the potential capacity in just the Québec region (160 GW [58]) surpasses the potential capacity of Colombia (56 GW). It is important to note that the Becancour's project generates 3000 ton-H_2/year which, for the installed capacity of 20 MW, requires a factor capacity of 85.6% (assuming a production yield of 50 kWh/kgH_2). Accordingly, this project works with a dedicated hydropower source. It is not based on electricity excedents.

4. Wind Power for Green H_2 Generation

Wind turbines emerged more than a century ago and are very attractive because they produce electricity by using the kinetic energy created by air in motion hitting the turbine blades. Nowadays, wind energy is one of the key sources of renewable energy and is becoming very attractive due to cost reductions. According to IRENA's most recent report [59], the LCOE of new onshore and offshore wind projects added in 2021 fell by 15% to USD 0.033/kWh and by 13% to USD 0.075/kWh, respectively. In the first case, this value is even lower than the one for Solar PV (USD 0.048/kWh). The total global installed capacity of onshore and offshore has jumped from 7.5 GW in 1997 to approximately 770 GW by 2021, which is an increase of almost 102 times [60].

Some challenges for implementing wind power for green H_2 generation include the following. The limitation of the wind–hydrogen electrochemical coupling system is due to the intermittent ability of the wind to produce electricity. Although operating electrolyzers in an intermittent way is technically viable [61], it is not recommended since it decreases the lifespan and efficiency of the electrolyzer.

In addition, considering the high investment cost, the economics of electrolyzers demand high utilization rates. Therefore, it is not economically competitive to produce H_2 from limited peaks of power [62,63]. This fact enhances the development of complementary distributed energy systems with different types of energy, operation modes, control equipment and its control strategy. In line with the above, an auxiliary power grid preferably with non-conventional renewable energy sources with high-capacity factors superior to wind/photovoltaic are recommended to ensure that the electrolyzer is functioning at full capacity.

4.1. Wind Potential in Colombia

The potential of wind energy generation is directly related to the wind speed and has been generally seen as a function of the power density (W/m^2). For the case of Colombia, as shown in Figure 4a, in La Guajira, located at the north zone of Colombia, there is a high density of wind power. For this reason, in 2004, the first wind farm with an installed capacity of 19.5 MW was deployed in this place and was still in operation initially until 2023 [64]. Currently, there are several projects in different phases that are already operating or that will be operating soon. Very recently, another onshore project in La Guajira, named Guajira 1, with an installed capacity of 20 MW started operation in January 2022 [65]. For the case of offshore projects, the city of Barranquilla is planning to develop a 350 MW project [66].

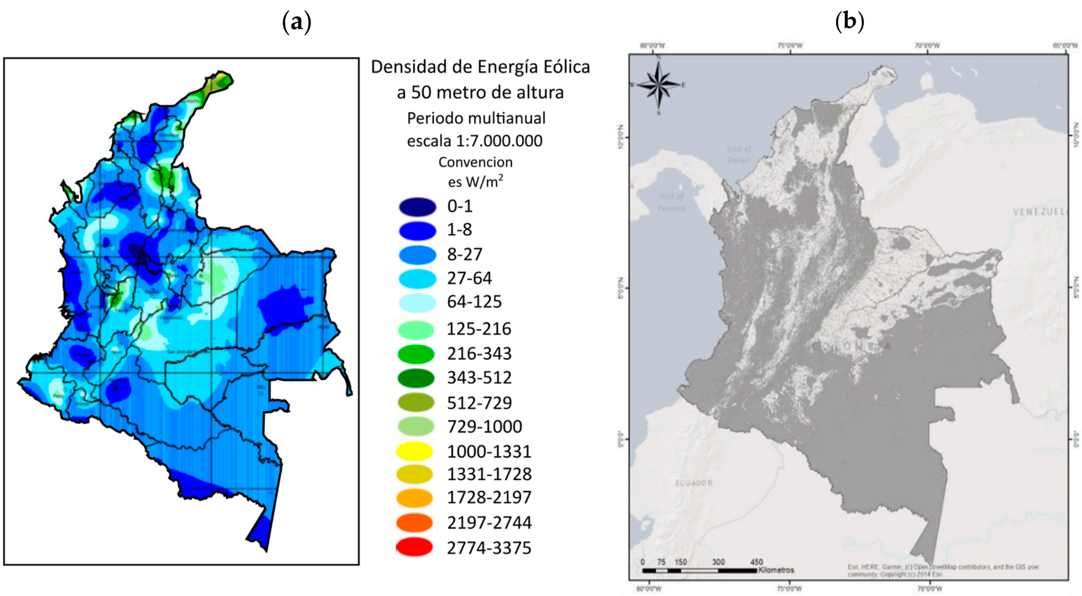


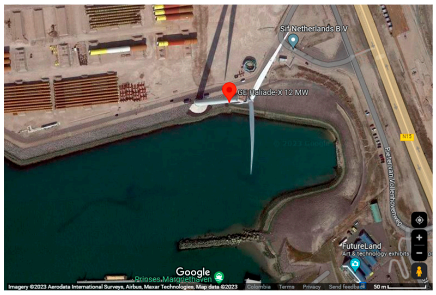
Figure 4. (**a**) Wind energy density of Colombia at a level of 50 m above the ground (UPME) [67]. (**b**) Areas with some restrictions for wind projects (dark gray) "Análisis espacial multicriterio para la ubicación de parques eólicos y granjas solares en Colombia" [32]. Figure 4b was taken from reference [32], which was published under Creative Commons CC BY-ND 4.0.

After a detailed analysis, considering not only the wind potential but relevant restrictions such as environmental and tourist restrictions, type of technology, distance to the electric grid, and some other factors [32], the areas to install wind projects are strongly reduced (Figure 4b) and the Colombian potential for onshore and offshore wind energy is estimated to total 67.8 GW (19 GW onshore and 48.8 GW offshore) [32], which could allow the generation of 172 TW/year. In terms of the CAPEX, for a 100 MW wind park, the value can range from USD 157 million to 188 million, while the LCOE can vary from 25 to 100 USD/MWh, depending on the location [32].

4.2. Case Study: Wind for Green H_2 Generation

The case study corresponds to the largest offshore wind-to-hydrogen plant in Europe. The generated hydrogen is planned to be transported through the HyTransPort pipeline (Table 7) [68].

Table 7. Case study: hydropower for green H_2 generation (image source: Imagery © Aerodata International Surveys, Airbus, Maxar Technologies, Map data © 2023).

Case Study Wind for Green H_2 Generation		
Project name	Rotterdam Offshore Wind Coalition	
Renewable energy source	Wind energy	
Location	Port of Rotterdam, the Netherlands	
Wind potential in the region	Constructing 5 to 7 wind farms in the 2016–2023 of at least 700 MW [69]	
Developer	Shell Nederland	
Location selection criteria	Reduction in CO_2 emissions and efficient use of raw materials and residues of the port	
Hydrolysis technology	proton exchange membrane electrolyzer	
Installed capacity	200 MW at least 150 MW of new wind power will be added	
Hydrogen production capacity	21.900 ton-H_2/year	
Project cost	Not available	
Deploy time	3 years (it will finish in 2025)	
Status	Under construction	
Hydrogen end-use	Supply the Shell Energy and Chemicals Park	
References	[68–72]	

The offshore wind potential of Rotterdam is around 900 W/m^2 [73], which is matched and even surpassed in Colombian Caribbean cities such as Barranquilla and Santa Marta in offshore conditions. The city Piyohureka in La Guajira also surpasses the Rotterdam potential in both onshore and offshore conditions.

5. Biomass for Green H_2 Generation

Biomass is a renewable energy source resulting from organic waste from humans, animals, crops and forestry. It is considered renewable because our society and nature will keep producing it. Biomass projects face several challenges including the following.

- Environmental: deforestation, biodiversity loss and land degradation. Basically, encouraging its production is controversial, since it implies generating more waste leading to the depletion of valuable resources such as water, soil and fertilizers. In addition, biomass processing and its usage generate greenhouse gas emissions such as CO_2 during direct combustion and methane when biomass is transformed into biogas. The biogas resulting from the anaerobic fermentation of biomass contains a mixture of methane (55–65%), CO_2 (30–45%) and traces of H_2S and water. All efforts to prevent methane reaching the atmosphere are justified, since its warming potential is 25 times that of CO_2 [74].
- Social: biomass as an energy source can compete with food production, leading to social conflicts.

- Legal: regulatory barriers associated with the lack of standardization.
- Technical: the solution is not scalable. It is limited by the availability of high-quality biomass (the biomass leading to high conversion efficiencies).

Table 8 shows the biomass transformation processes by biological and thermochemical routes and the final products generated. Accordingly, compared to other carbon-based energy resources such as natural gas or coal, biomass is a neutral-carbon renewable alternative that plays an important role as a transition resource toward a fully decarbonized energy supply.

Table 8. Main routes to acquire hydrogen from biomass [75].

Category	Process	Subprocesses	Final Products
Biological	Anaerobic digestion	-	H_2/CO_2
		Reforming shift	H_2/CO_2
		Pyrolysis	H_2/C
	Fermentation	Reforming shift	H_2/CO_2
	Metabolic processing	Photobiology	H_2/O_2
		Bioshift	H_2/CO_2
Thermochemical	Gasification	Bioshift	H_2/CO_2
		Shift	H_2/CO_2
		Synthesis → Reforming shift	H_2/CO_2
		Reforming shift	H_2/CO_2
	High-pressure aqueous	-	H_2/CO_2
		Reforming shift	H_2/CO_2
	Pyrolysis	Severe	H_2/C
		Reforming shift	H_2/CO_2

An intense debate has surged around considering green hydrogen generated from biomass. Clearly, the main routes for transforming biomass into H_2 (Table 8) do not completely fit any of the definitions of green hydrogen presented in the introduction. Firstly, the transformation of biomass into H_2 is not achieved by the direct application of renewable electricity. Secondly, most of these methods yield to CO_2 emissions, which is in many cases over 4.37 kg-CO_2/kg-H_2. The only alternatives not generating CO_2 are the photobiology route (which is still in an early research stage [76]) and pyrolysis. In particular, the pyrolysis of methane leads to "turquoise hydrogen" where solid carbon is produced with carbon capture rates reaching up to 95%. In the future, turquoise hydrogen may be valued as a low-emission hydrogen if the energy source for the thermal process is powered with renewable energy and the carbon is permanently stored [77].

Remarkably, producing a unit of hydrogen from the electrolysis of water requires four times more energy than from hydrocarbons [78], and that is why the green hydrogen concept should be expanded to include other clean hydrogen production pathways beyond electrolysis [79]. Even the European Commission admits that the biomass gasification has not been assigned a color, although its usage for hydrogen production is not a new process [79].

5.1. Biomass Potential in Colombia

The Unidad de Planeación Minero Energetica (UPME) estimated the total biomass potential in the country to be around 450.000 TJ/year [80] which is equivalent to 125,100 GWh/year with a 14.27 GW average power generation. This biomass potential is mainly produced by agricultural crop residue (73.62%) and animal manure (26.24%). The distribution of the total biomass in the country is shown in Figure 5 [81].

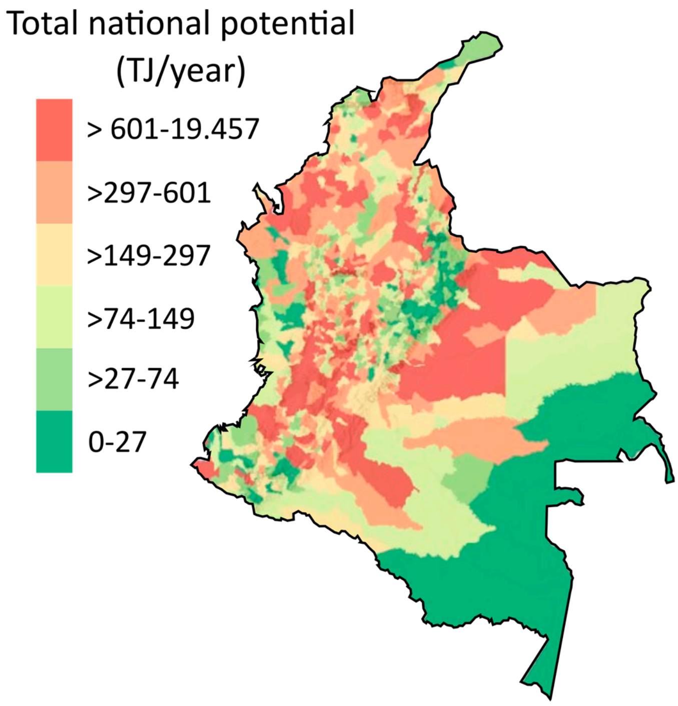


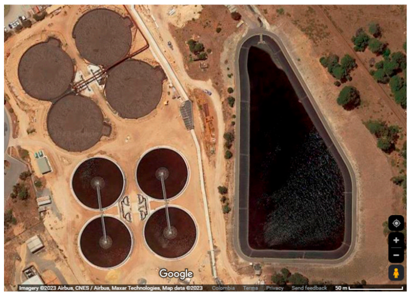
Figure 5. Total biomass potential in Colombia (units: TJ/year). Sources: Esri, USGS | Esri, HERE, Garmin, FAO, NOAA, USGS | UPME [81].

5.2. Case Study: Biogas for Green H_2 Generation

Turquoise hydrogen is an outstanding strategy toward reaching the goal of low-emissions hydrogen. Several companies are pursuing the generation of this turquoise hydrogen including C-Zero [82], Pure hydrogen corporation [83], BASF/RWE [84], Port Moody B.C. [85] and Hazer [86]. All these examples correspond to pilot plants currently under construction. Interestingly, the solid carbon generated during the process can find application for instance in electronics as shown by GMG graphene for the development of the novel aluminum–ion batteries [87,88]. The Hazer group pilot plant was selected as a case study as follows (Table 9).

In the Colombian case, there are several wastewater treatments plants (PTAR) that could be potentially used to generate green hydrogen. This is the case of Aguas Claras PTAR located in the Aburra Valley (Antioquia), which can generate an average of 12.7 million m^3/year of biogas. Considering the case study, Aguas Claras could potentially produce 400 Ton-H_2/year (assuming 63% of methane in the biogas) and 1548 Ton per year of battery-grade hard carbon.

Table 9. Case study: biogas for green H_2 generation (image source: Imagery ©Airbus, CNES/Airbus, Maxar technologies, Map data © 2023).

Case Study **Biogas for Green H_2 Generation**	
Project name	Hazer commercial demonstration project 
Renewable energy source	- Biogas from the Woodman Point Wastewater Treatment Plant. 2 million m^3/year - Heating from electricity and non-reacted biogas.
Location	Pert, Australia
Biogas potential in the region	Approximately 6.18 million Nm^3/year (since the electrical capacity of the plant is 1200 kW and assuming that typically 1 m^3 biogas is equivalent to 1 $kW_{el}h$)
Developer	Hazer Group and the Water Corporation
Location selection criteria	Access to biogas from water treatment plant
Catalyst technology	Iron–ore catalyst. 1 kg of catalyst consumed for every 15 kg of methane feedstock, iron–ore costs approximately USD 0.04 USD per kg of hydrogen produced.
Hydrogen production capacity	- 100 ton-H_2/year (estimated); - 375 ton-graphite/year (estimated). Since it is battery-grade, it can be sold at USD 200–1000 per ton
Project cost	USD 18.7 million
Deploy time	15 months March 2021–June 2022
Status	Operating
Hydrogen end-use	H_2 for industry
Initial cost of produced hydrogen	$2.9 USD/kg-$H_2$
References	[89–91]

6. Other Energies for Green H_2 Generation in Colombia

In Colombia, there are other emerging renewable sources such as geothermal and ocean energy (tidal, wave and salinity gradient), which can be evaluated as alternatives for hydrogen generation. In the case of geothermal energy, its potential has been estimated to be around 1.17 GW [92], where the highest percentage is present in volcanic systems located in protected areas of the country, such as the Nevado del Ruiz, the Nevado del Huila, and Cerro Bravo volcano [93]. This resource has been mainly considered to provide energy to regions with low population and not for large projects due to its low potential and the restrictions to develop energy projects in protected environments. Therefore, the geothermal alternative does not seem to be a viable option for hydrogen generation in the short term.

In the case of ocean energy, there is a high interest in the Colombian Pacific, since this resource has greater power per unit area than the rest of the renewable energies, presenting 2000–3000 W/m^2, which is compared with solar or wind, which present 200 W/m^2 and 400–600 W/m^2. In fact, the ocean energy offers advantages such as a relatively high capacity factor (20–35%) and predictability [94], which has led to some demonstrations of green hydrogen generation [95]. However, the potential of the ocean energy in Colombia is uncertain, since no atlas are publicly available. In addition, experiences around the world have demonstrated that this technology is still in a very early development stage, and few technologies have reached commercialization [96] production costs at commercial scale, which adds to the risk of disrupting the coastal ecology [97]. So, it is more feasible to use the other energy resources discussed in the previous sections.

7. General Overview

Colombia has one of the cleanest electric energy grids thanks to the production of hydroelectricity, which covers most of the electric energy demand. However, the overall energy matrix is still carbon intensive with around 80% of the total energy supply coming from fossil fuels. Industry and transport sectors demand a huge amount of energy, which is covered by liquid fuels or natural gas (Table 1). Internal combustion engines and equipment for the generation of thermal energy in industry account for most of the fossil fuels demand. The electrification of these economic sectors would imply a total technological conversion to electric engines, which is not viable in the near term. In this context, hydrogen constitutes an alternative for energy storage and transport to be used in economic activities that are hard to decarbonize. Table 10 summarizes the potential for hydrogen production, the projected and installed capacity of renewable energy sources according to the Colombian government and some economic and environmental figures of merit discussed in this work.

Table 10. Figures of merit of renewable energy sources for hydrogen production and some key economic and environmental indicators [6,98–100].

Figure of Merit	Renewable Energy Source			
	Solar	Wind	Hydro	Biomass
Potential power capacity (GW)	8172	19 [a] 48.8 [b]	56	14.27
Installed power capacity (GW)	0.741	0.018	11.97	0.193
Capacity of new projects to be operative in 2027 (GW)	10.2	2.73	2.77	0.028
Potential of H_2 production (kton/year) [c]	286,346	1272 [a] 4080 [b]	4328	2453
LCOH (USD/kgH_2) for 2020	5.6	2.8 [a] 4.5 [b]	3.41	2.9–4.4 [d]
LCOH (USD/kgH_2) for 2050	1.7	1.5 [a] 2.2 [b]	3.09 [e]	1.4–1.8 [d]
Carbon intensity estimated for Colombia (kgCO_2-eq/kgH_2)	3.9	0.8	1.02	−9.8–26 [f]

[a]. Onshore wind energy [b]. Offshore wind energy [c]. For the potential H_2 production, the following assumptions were made: 1. capacity factors of 20%, 39%, 49%, and 45% for solar, onshore and offshore wind and hydropower, respectively. 2. Electrolyzers for green hydrogen production yield 50 kWh/kgH_2 [d]. Range of LCOH depending on the technology used for H_2. production from biomass. [e]. Not available. It was estimated using the LCOE for hydropower which is expected to reduce on average 9.4% by 2050 [101]. [f]. Range of carbon intensity depending on the biomass source and the incorporation of CCUS technologies.

Table 10 indicates that hydropower accounts for most of the installed power capacity in Colombia (67%), while wind and solar constitute less than 1%, and the rest is thermoelectric. Consequently, electrolysis powered by hydraulic energy is promising for the early stage of deployment of green hydrogen production. Despite the huge potential of solar and wind energy generation given by the resource availability, the country is just starting the projects for power generation with these sources. If all the projects currently registered to be operative by 2027 are successfully concluded, solar and wind electricity will account for 32% and 8% of the electric energy supply, respectively. Given the lower LCOH projected for green hydrogen powered by wind energy, its wide implementation is likely expected for the next decade. In addition, beyond 2030, it is expected that the LCOH for green hydrogen derived from solar energy will continuously fall to 1.7 USD/kgH_2 by 2050. The expected increase in installed capacity of solar power along with the decrease in the expected LCOH holds promise for an important growth of hydrogen production by solar water electrolysis. Indeed, a recent prospective analysis states that a power capacity of 7.59 GW is required to meet Colombia's hydrogen demand. The optimal distribution of sources of energy to minimize the cost and emissions includes solar power (65.8%), onshore wind (28.1%), and the rest (6.1%) with blue hydrogen from natural gas reforming with CCUS. From the maps shown in this work, the most promising regions for hydrogen production are east, central and north. Specifically, the departments of Arauca, Vichada, Casanare and Meta in the east, and Guajira, Atlántico, and Bolivar in the north meet the requirements. Despite the huge availability of energy in these regions, a deeper analysis of water resources needs to be carried out given that 9 L of water are needed per kg of H_2 produced. Finally, the assessment of the actual hydrogen projects in the country (Table 11) indicates a trend toward using solar and hydropower sources. This fact fully aligns with the previous analysis of the potential pathways toward the massive generation of green hydrogen.

Table 11. Main proposed green hydrogen projects in the country.

Company	Location	Electrolyzer Technology	Renewable Energy Source	Investment (Million USD)	Production Capacity (kg-H_2/Year)	Ref
OPEX-Hevolution	Andes	Alkaline 2 MW	Hydropower	$10	365.000	[102,103]
Promigas	Cartagena	PEM 53.2 kW	Solar 137 kW	$1.2	1574	[104,105]
Ecopetrol	Cartagena	PEM 50 kW	Solar 85 kW	$6	7300	[106,107]
Hub H_2 verde Manizales (Solenium. H_2 Andes, HPSG)	Manizales	1 MW	Solar 3 MW	$6	146.000	[108,109]
Universidad de la Guajira—Alianza SENECA	Riohacha	Alkaline	Solar 10 kW	$0.04	548 *	-
Universidad de la Guajira—Alianza SENECA	Riohacha	Alkaline	Wind 5 kW	$0.02	378 *	-

* Estimated value using 50 kWh/kg-H_2 equivalence.

In Colombia, the current demand for H_2 is estimated at 155 kiloton H_2/year, which is supplied by gray or black hydrogen. This annual demand is distributed among the refinery sector (84%), fertilizers (12%) and other industries (4%) such as hydrogenated fats. By the year 2050, the demand is expected to reach 1867,65 kiloton H_2/year mainly distributed between the industry (33%) and the transport (64%) sectors [6]. In order to harness the potential of renewable energy resources and facilitate the production of cleaner hydrogen to fulfill this growing demand, Colombia has methodically executed a series of national policies designed to propel a more environmentally sustainable energy transition. Between the years 2014 and 2018, the significant integration of Unconventional Renewable Energy Sources (URES) into the country's energy landscape through the enactment of Law 1715 and its subsequent inclusion in the National Energy Plan (NEP) is noteworthy [18,110]. In addition, in the year 2019, a notable stride toward sustainability in mobility materialized through Legislation 1964 [111], which advocated for the adoption of electric and zero-emission vehicles. This commitment to transitioning toward cleaner energies reached a pivotal juncture in 2021 with the enactment of Law 2099 [112], formally recognizing the status of URES for green hydrogen. This measure established an ambitious roadmap charting specific objectives for the year 2030 [113]. It is anticipated that these actions will exert a substantial impact on reducing CO_{2eq} emissions, with an estimated potential of up to 3 megatons [113,114]. Furthermore, to incentivize industry participation, notable fiscal incentives have been implemented, including a 50% discount in income taxes, exemption from VAT and tariffs for URES-related projects, coupled with tax incentives for their implementation [18,112]. Concurrently, a strategic installation of a minimum of 50 public hydrogen refueling stations (hydrogen stations) is envisaged across the Colombian territory. There is a projection to replace 40% of black and gray hydrogen used in industry with cleaner alternatives, such as green and blue hydrogen. Additionally, an ambitious production target of 50 kilotons of blue hydrogen has been delineated, which is accompanied by the deployment of an electrolysis capacity ranging from 1 to 3 Gigawatts (GW) earmarked for green hydrogen production [113,114]. These collective endeavors buttress and catalyze the escalating adoption of hydrogen as an essential energy source and sustainable energy storage solution within the Colombian energy landscape.

8. Conclusions

Colombia has the capability to produce clean low-cost electricity, typically from hydropower and recently also from solar and wind resources, which in combination with an ambitious plan to reach 3 GW of dedicated electrolyzer capacity by 2030 and wide access to water has demonstrated the potential of the country to produce some of the cheapest green hydrogen in the world according to the IRENA. An assessment of the realistic potential of solar photovoltaics, hydropower, wind, and biomass was found to reach 8172 GW, 56 GW, 68 GW and 14 GW, respectively. In addition to the potential of the natural resources of the country to generate clean electricity, this work presented emblematic case studies around the world that demonstrate their technical and economic feasibility in Colombia. Remarkably, in the short term, the regions of the country with access to hydropower (e.g., Andean region) are expected to dominate the green hydrogen generation since hydropower is much more developed in the country than the other sources of renewable energy. It is important to note that there is currently a strong debate around the idea of using just new hydropower projects to generate hydrogen to protect the national electric system. However, simple action plans such as increasing the capacity factor of the existing hydropower plants would enable the generation of green hydrogen exploiting surplus energy. In the long term, regions with a wider access to solar and wind resources (e.g., the north and east regions) will benefit from the reduced levelized cost of electricity of these technologies. Presently, Colombia boasts noteworthy instances of flourishing green hydrogen projects that serve as demonstrative illustrations of the extensive opportunities and propitious scenarios that lie ahead in the imminent energy transition. This is further fortified by the country's dedicated endeavor to institute policies aimed at nurturing green hydrogen, elevating its status to that of a commercially sustainable alternative poised to effectively cater to the nation's domestic energy requirements.

Author Contributions: Conceptualization, J.J.P., E.R., R.B., J.F.M. and F.J.; Methodology, J.J.P., E.R., R.B. and J.F.M.; Validation, J.J.P., P.R.-G., A.M.K., P.E. and F.J.; Formal analysis, J.J.P., E.R., R.B. and J.F.M.; Investigation, R.B. and F.J.; Writing—original draft, J.J.P., C.V. and E.R.; Writing—review & editing, E.C., A.M.K. and D.R.; Supervision, F.J. All authors have read and agreed to the published version of the manuscript.

Funding: We gratefully acknowledge the financial support provided by the Colombia Scientific Program within the framework of the call Ecosistema Científico (contract no. FP44842—218–2018).

Data Availability Statement: In this research several data sources were used including hydrogen color classification [6,7]; global solar atlas [15]; maps of restricted areas for solar and wind projects [32], hydropower potential [48,49]; wind energy density [67]; total biomass potential [81]; and figures of merit of renewable energy sources for hydrogen production and key economic and environmental indicators [6,98–100].

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

References

1. Jaramillo, C.; Escobar, L. *Proyección de Demanda de Energéticos*; Unidad de Planeación Minero Energética (UPME): Bogotá, Colombia, 2022.
2. Ritchie, H.; Roser, M. Energy. Available online: https://ourworldindata.org/energy (accessed on 5 November 2022).
3. Escobar, F.A. 1992: El año del Apagón. Available online: https://www.senalmemoria.co/articulos/apagon-ano-1992 (accessed on 30 October 2022).
4. US Department of Energy. H2@Scale. Available online: https://www.energy.gov/eere/fuelcells/h2scale (accessed on 12 October 2022).
5. International Energy Agency. The Future of Hydrogen: Seizing Today's Opportunities. Available online: https://www.iea.org/reports/the-future-of-hydrogen (accessed on 12 October 2022).
6. Ágel, M.; Botet, C.; Cuello, N.; Laverde, M. *Recomendaciones Para el Desarrollo de la Economía del Hidrógeno en Colombia: Una Estrategia Nacional de Hidrógeno*; Primera, Ed.; Universidad de La Sabana: Chía, Colombia, 2022.
7. World Energy Council. National Hydrogen Strategies. Available online: https://www.worldenergy.org/assets/downloads/Working_Paper_-_National_Hydrogen_Strategies_-_September_2021.pdf (accessed on 10 October 2022).

8. Ministerio de Minas y Energía. *Decreto 1476*; Ministerio de Minas y Energía: Bogotá, Colombia, 2022.
9. Actualización del Costo Nivelado de Energía (LCOE) Para 1er Semestre de 2021. Available online: https://www.bloomberg.com/latam/blog/actualizacion-del-costo-nivelado-de-energia-lcoe-para-1er-semestre-de-2021/ (accessed on 12 October 2022).
10. Shahabuddin, M.; Krishna, M.M.; Bhaskar, T.; Perkins, G. Advances in the thermo-chemical production of hydrogen from biomass and residual wastes: Summary of recent techno-economic analyses. *Bioresour. Technol.* **2020**, *299*, 122–557. [CrossRef] [PubMed]
11. Reed, J. UC Office of the President Can Green Hydrogen Be a Cost Competitive Transportation Fuel by 2030? *Calif. Digit. Libr. Univ. Calif.* **2022**, *1*, 1–5. [CrossRef]
12. Micena, R.P.; Llerena, O.R.; De Souza, T.M.; Silveira, J.L. Solar-powered Hydrogen Refueling Stations: A techno-economic analysis. *Int. J. Hydrogen Energy* **2020**, *45*, 2308–2318. [CrossRef]
13. The World Bank. What a Waste 2.0. Available online: https://datatopics.worldbank.org/what-a-waste/ (accessed on 10 November 2022).
14. Abbott, D. Keeping the energy debate clean: How do we supply the world's energy needs? *Proc. IEEE* **2010**, *98*, 42–66. [CrossRef]
15. World Bank Group. Global Solar Atlas. Available online: https://globalsolaratlas.info/map?c=10.943357,16.233488,3 (accessed on 25 October 2022).
16. Rodríguez, D.; Rodríguez, L. Photovoltaic energy in Colombia: Current status, inventory, policies and future prospects. *Renew. Sustain. Energy Rev.* **2018**, *92*, 160–170. [CrossRef]
17. IRENA; USAID. *Renewable Energy Auctions in Colombia: Context, Design and Results*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2021.
18. Congreso de Colombia. *Ley 1715 de 2014*; Departamento Administrativo de la Función Pública: Bogotá, Colombia, 2014.
19. Urrego, A. En Los Próximos Tres Años, 10 Empresas Podrán en Operación Nuevas Granjas Solares. Available online: https://www.larepublica.co/empresas/en-los-proximos-dos-anos-10-empresas-podran-en-operacion-nuevas-granjas-solares-3346288 (accessed on 15 October 2022).
20. Ministerio de Minas y Energía. Transición Energética: Un Legado Para el Presente y el Futuro de Colombia. Available online: www.laimprentaeditores.com (accessed on 1 November 2022).
21. Ministerio de Minas y Energía. Diálogo Social Para Definir la Hoja de Ruta Para la Transición Energética Justa en Colombia. Available online: https://bit.ly/HojaRutaTransicionEnergeticaJustaCO (accessed on 1 October 2022).
22. Kim, J.H.; Hansora, D.; Sharma, P.; Jang, J.W.; Lee, J.S. Toward practical solar hydrogen production—An artificial photosynthetic leaf-to-farm challenge. *Chem. Soc. Rev.* **2019**, *48*, 1908–1971. [CrossRef]
23. Wang, Q.; Domen, K. Particulate Photocatalysts for Light-Driven Water Splitting: Mechanisms, Challenges, and Design Strategies. *Chem. Rev.* **2020**, *120*, 919–985. [CrossRef]
24. Luo, S.; Ren, X.; Lin, H.; Song, H.; Ye, J. Plasmonic photothermal catalysis for solar-to-fuel conversion: Current status and prospects. *Chem. Sci.* **2021**, *12*, 5701–5719. [CrossRef]
25. Sharma, A.; Arya, S.K. Hydrogen from algal biomass: A review of production process. *Biotechnol. Rep.* **2017**, *15*, 63–69. [CrossRef]
26. Pregger, T.; Graf, D.; Krewitt, W.; Sattler, C.; Roeb, M.; Möller, S. Prospects of solar thermal hydrogen production processes. *Int. J. Hydrogen Energy* **2009**, *34*, 4256–4267. [CrossRef]
27. Hisatomi, T.; Domen, K. Reaction systems for solar hydrogen production via water splitting with particulate semiconductor photocatalysts. *Nat. Catal.* **2019**, *2*, 387–399. [CrossRef]
28. Grimm, A.; De Jong, W.A.; Kramer, G.J. Renewable hydrogen production: A techno-economic comparison of photoelectrochemical cells and photovoltaic-electrolysis. *Int. J. Hydrogen Energy* **2020**, *45*, 22545–22555. [CrossRef]
29. Polman, A.; Knight, M.; Garnett, E.C.; Ehrler, B.; Sinke, W.C. Photovoltaic materials: Present efficiencies and future challenges. *Science* **2016**, *352*, aad4424. [CrossRef] [PubMed]
30. Eljack, F.; Kazi, M.K. Prospects and Challenges of Green Hydrogen Economy via Multi-Sector Global Symbiosis in Qatar. *Front. Sustain.* **2020**, *1*, 612762. [CrossRef]
31. Ariza, M.F.; Mwanza, M.; Çetin, N.S.; Ülgen, K. Assessment of the energy generation potential of photovoltaic systems in Caribbean region of Colombia. *Period. Eng. Nat. Sci.* **2017**, *5*, 55–60. [CrossRef]
32. Orrego, S.G. Análisis Espacial Multicriterio Para la Ubicación de Parques Eólicos y Granjas Solares en Colombia. Available online: https://repositorio.unal.edu.co/handle/unal/79490 (accessed on 29 September 2022).
33. Romero, I.; Franco, B. *La oportunidad de negocio de la Generación Solar Distribuida en Colombia*; Generación Sole; Programa de las Naciones Unidas para el Medio Ambiente (PNUMA): Clayton, Panama, 2021; pp. 1–180. Available online: https://ser-colombia.org/wp-content/uploads/2021/11/Generacio%CC%81n-Sole-Financiamiento-GDS-Col.pdf (accessed on 29 September 2022).
34. DANE. ¿Dónde Estamos? Available online: https://www.dane.gov.co/index.php/estadisticas-por-tema/demografia-y-poblacion/censo-nacional-de-poblacion-y-vivenda-2018/donde-estamos (accessed on 3 October 2022).
35. Sireagroup. Green Hydrogen: With Photovoltaics, We Will Produce Our Own Hydrogen. Available online: https://www.sireagroup.com/en/2021/03/22/green-hydrogen-photovoltaics/ (accessed on 3 October 2022).
36. Meneses, E. Chile Produce su Primera Molécula de Hidrógeno Verde Para Minería. Available online: https://www.rumbominero.com/peru/noticias/internacionales/chile-produce-su-primera-molecula-de-hidrogeno-verde-para-mineria/ (accessed on 4 October 2022).

37. Collins, L. Shanghai Goes All-in on Hydrogen, with Plans for H2 Port, Pipelines and Trading Platform. Available online: https://www.rechargenews.com/energy-transition/shanghai-goes-all-in-on-hydrogen-with-plans-for-h2-port-pipelines-and-trading-platform/2-1-1288034 (accessed on 10 October 2022).
38. Pinedo, E.; Carreño, B. France, Spain and Portugal Agree to Build Barcelona-Marseille Gas Pipeline. Available online: https://www.reuters.com/business/energy/spain-france-portugal-agree-new-energy-route-pm-sanchez-says-2022-10-20/ (accessed on 4 November 2022).
39. IBERDROLA. Iberdrola Instala la Mayor Planta de Hidrógeno Verde Para Uso Industrial en Europa. Available online: https://www.iberdrola.com/conocenos/nuestra-actividad/hidrogeno-verde/puertollano-planta-hidrogeno-verde (accessed on 6 November 2022).
40. El digital CLM. Castilla-La Mancha es la Comunidad con Más Energía Fotovoltaica Instalada en 2022. Available online: https://www.elespanol.com/eldigitalcastillalamancha/region/20220519/castilla-la-mancha-comunidad-energia-fotovoltaica-instalada/673683125_0.html (accessed on 6 November 2022).
41. World Energy Trade. Iberdrola Abre la Mayor Planta de Hidrógeno Verde de Europa Dirigida al Sector Industrial. Available online: https://www.worldenergytrade.com/energias-alternativas/gas/iberdrola-mayor-planta-hidrogeno-verde-europa (accessed on 6 November 2022).
42. Jaganmohan, M. Cumulative Hydropower Capacity Worldwide in 2021, by Major Country. Available online: https://www.statista.com/statistics/474652/global-total-hydropower-capacity-in-major-countries/#statisticContainer (accessed on 25 October 2022).
43. IHA. Hydropower Status Report 2022. Available online: https://www.hydropower.org/sites/default/files/publications-docs/2019_hydropower_status_report_0.pdf (accessed on 2 November 2022).
44. IRENA. Renewable Power Generation Costs in 2014: Hydropower 2010. IRENA, 2014; Volume 1, pp. 113–123. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2015/IRENA_RE_Power_Costs_2014_report.pdf (accessed on 2 November 2022).
45. IEA. Hydrogen. Available online: https://www.iea.org/reports/hydrogen (accessed on 2 November 2022).
46. IHA. The Green Hydrogen Revolution: Hydropower's Transformative Role. IHA, 2021; Volume 1, no. May. pp. 1–8. Available online: https://www.hydropower.org/publications/the-green-hydrogen-revolution-hydropowers-transformative-role (accessed on 3 November 2022).
47. Cano, S.L. Challenges for a Just Energy Transition in Andean Economies. l'université Sorbonne Nouvelle. Master's Thesis. 2021, pp. 1–155. Available online: https://dumas.ccsd.cnrs.fr/dumas-04136491/document (accessed on 3 November 2022).
48. UPME. *Evaluación del Potencial Hidroenergético a Pequeña Escala en Cuencas Hidrológicas con un Modelo Lluvia-Escurrimiento: Capítulo 4 EVALUACIÓN DEL POTENCIAL HIDROENERGÉTICO*; Central Urrá: Cordoba, Colombia, 2015; pp. 73–110.
49. Esri. ArcGIS Online. Available online: https://www.arcgis.com/home/webmap/viewer.html?url=https://geo.upme.gov.co/server/rest/services/UPME_PE/Potencial_Hidroenerg%25C3%25A9tico_por_subzona_hidrogr%25C3%25A1fica_Lc_1_kil%25C3%25B3metro/FeatureServer&source=sd (accessed on 30 October 2022).
50. Posso, F.; Espinoza, J.L.; Sánchez, J.; Zalamea, J. Hydrogen from hydropower in Ecuador: Use and impacts in the transport sector. *Int. J. Hydrogen Energy* **2015**, *40*, 15432–15447. [CrossRef]
51. Thapa, B.S.; Neupane, B.; Seong, H.; Lee, Y.H. Green hydrogen potentials from surplus hydro energy in Nepal. *Int. J. Hydrogen Energy* **2021**, *46*, 22256–22267. [CrossRef]
52. IEA. Hydrogen Projects Database. Available online: https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database (accessed on 30 October 2022).
53. FuelCellsWorks. Air Liquide and Cummins Go All-In on Green Hydrogen. FuelCellsWorks, 2020. Available online: https://fuelcellsworks.com/news/air-liquide-and-cummins-go-all-in-on-green-hydrogen/ (accessed on 30 October 2022).
54. Edwardes-Evans, H. Air Liquide Completes 20 MW Canadian Electrolysis Plant. Available online: https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/electric-power/012621-air-liquide-completes-20-mw-canadian-electrolysis-plant (accessed on 15 October 2022).
55. Air Liquide. Air Liquide Inaugurates the World's Largest Low-Carbon Hydrogen Membrane-Based Production Unit in Canada. Available online: https://www.airliquide.com/group/press-releases-news/2021-01-26/air-liquide-inaugurates-worlds-largest-low-carbon-hydrogen-membrane-based-production-unit-canada (accessed on 15 October 2022).
56. *Bécancour PEM Green Hydrogen Plant*; Nomination for ACEC Award: Project Management Category; Ais Liquide: Bécancour, QC, Canada; Hatch: Mississauga, ON, Canada, 2021; pp. 1–7.
57. cummins.com. Cummins HyLYZER-1000 Water Electrolysis Specification Sheet. Available online: https://www.cummins.com/sites/default/files/2021-08/cummins-hylyzer-1000-specsheet.pdf (accessed on 17 October 2022).
58. Canadian Hydropower Association. Canadian Hydro Capacity and Potential (MW). Available online: https://canadahydro.ca/wp-content/uploads/2015/09/CHA-map-Capacity-Potential-2015-v6.pdf (accessed on 17 October 2022).
59. Abu, D. *Renewable Power Generation Costs in 2020*; IRENA: Abu Dhabi, United Arab Emirates, 2021.
60. IRENA. Wind Energy. Available online: https://www.irena.org/Energy-Transition/Technology/Wind-energy (accessed on 3 November 2022).
61. Fang, R.; Liang, Y. Control strategy of electrolyzer in a wind-hydrogen system considering the constraints of switching times. *Int. J. Hydrogen Energy* **2019**, *44*, 25104–25111. [CrossRef]

62. Mikovits, C.; Wetterlund, E.; Wehrle, S.; Baumgartner, J.; Schmidt, J. Stronger together: Multi-annual variability of hydrogen production supported by wind power in Sweden. *Appl. Energy* **2021**, *282*, 116082. [CrossRef]
63. McKenna, R.C.; Bchini, Q.; Weinand, J.M.; Michaelis, J.; König, S.; Köppel, W.; Fichtner, W. The future role of Power-to-Gas in the energy transition: Regional and local techno-economic analyses in Baden-Württemberg. *Appl. Energy* **2018**, *212*, 386–400. [CrossRef]
64. EPM. Parque Eólico Jepírachi. Available online: https://www.epm.com.co/site/home/nuestra-empresa/nuestras-plantas/energia/parque-eolico (accessed on 3 November 2022).
65. Urrego, A. Gobierno inauguró Guajira 1, el primer parque eólico que aportará 20 MW de energía. Available online: https://www.larepublica.co/economia/gobierno-inaugurara-hoy-el-parque-eolico-guajira-1-el-mas-grande-de-colombia-3289884 (accessed on 3 November 2022).
66. Buljan, A. Colombia Opens Up for Offshore Wind, CIP Enters with 350 MW Project. Available online: https://www.offshorewind.biz/2022/03/08/colombia-opens-up-for-offshore-wind-cip-enters-with-350-mw-project/ (accessed on 4 November 2022).
67. Ministerio de Minas y Energía. *Atlas del Viento y Energía Eólica*; Ministerio de Minas y Energía: Bogotá, Colombia, 2006; Chapter 4; pp. 75–102. ISBN 9588067170.
68. Memija, A. Shell to Start Building Europe's Largest Offshore Wind-to-Hydrogen Plant in Netherlands (Video). Available online: https://www.offshorewind.biz/2022/07/06/shell-to-start-building-europes-largest-offshore-wind-to-hydrogen-plant-in-netherlands-video/ (accessed on 4 November 2022).
69. Port of Rotterdam. Rotterdam Offshore Wind Coalition. Available online: https://www.portofrotterdam.com/en/setting/location-options/offshore/rotterdam-offshore-wind-coalition (accessed on 5 November 2022).
70. REUTERS. Shell to Start Construction of Renewable Hydrogen Plant in Netherlands. Available online: https://www.reuters.com/business/energy/shell-start-construction-renewable-hydrogen-plant-netherlands-2022-07-06/ (accessed on 5 November 2022).
71. Shell Global. Shell to Start Building Europe's Largest Renewable Hydrogen Plant. Available online: https://www.shell.com/media/news-and-media-releases/2022/shell-to-start-building-europes-largest-renewable-hydrogen-plant.html (accessed on 5 November 2022).
72. Aparicio, I.; Eecen, P.; Telsnig, T.; Vazquez, C. Annual progress report on SET-Plan offshore wind. *Deliverable* **2020**, *1*, 1–34.
73. World Bank Group; ESMAP; VORTEX; DTU. Global Wind Atlas. Available online: https://globalwindatlas.info/en/area/Netherlands (accessed on 5 November 2022).
74. EPA. Importance of Methane. Available online: https://www.epa.gov/gmi/importance-methane (accessed on 4 November 2022).
75. Milne, T.; Elam, C.; Evans, R. *Hydrogen from Biomass State of the Art and Research Challenges*; International Energy Agency Agreement on the Production and Utilization of Hydrogen; National Renewable Energy Lab. (NREL): Golden, CO, USA, 2002.
76. U.S. Departament of Energy. Hydrogen Production: Photobiological. Available online: https://www.energy.gov/eere/fuelcells/hydrogen-production-photobiological (accessed on 4 November 2022).
77. Nationalgrid. The Hydrogen Colour Spectrum. Available online: https://www.nationalgrid.com/stories/energy-explained/hydrogen-colour-spectrum (accessed on 4 November 2022).
78. Brandon, N.P.; Kurban, Z. Clean energy and the hydrogen economy. Philosophical Transactions of the Royal Society a Mathematical. *Phys. Eng. Sci.* **2017**, *17*, 20160400. [CrossRef]
79. EQTEC. How Biomass Gasification can Help Boost Global Green Hydrogen Production. Available online: https://eqtec.com/how-biomass-gasification-can-help-boost-global-green-hydrogen-production/ (accessed on 4 November 2022).
80. González, T.; Valencia, J.; UPME. *Integración de las Energías Renovables no Convencionales en Colombia*; UPME: Bogotá, Colombia, 2015.
81. Esri. ArcGis. Available online: https://www.arcgis.com/home/webmap/viewer.html?url=https://geo.upme.gov.co/server/rest/services/BIOMASA/Potencial_total_nacional_tj_A%25C3%25B1o/MapServer&source=sd (accessed on 4 November 2022).
82. C | Zero. Decarbonizing Natural Gas. Available online: https://www.czero.energy/ (accessed on 5 November 2022).
83. Pure Hydrogen "Pure Hydrogen". Available online: https://purehydrogen.com.au/news/ (accessed on 8 November 2022).
84. Raaijen, W. HYTE: Pilot plant turquoise hydrogen at BASF in Ludwigshafen. Available online: https://www.industryandenergy.eu/hydrogen/hyte-pilot-plant-turquoise-hydrogen-at-basf-in-ludwigshafen/ (accessed on 8 November 2022).
85. Ball, D.P. Cutting-Edge Hydrogen Power Project Planned for Port Moody Social Sharing. Available online: https://www.cbc.ca/news/canada/british-columbia/hydrogen-power-project-pilot-port-moody-bc-1.6510422 (accessed on 8 November 2022).
86. ARENA. The Hazer Process: Commercial Demonstration Plant. Available online: https://arena.gov.au/projects/the-hazer-process-commercial-demonstration-plant/ (accessed on 8 November 2022).
87. Urade, A. Integrating Sustainability into Graphene Nanomaterial Synthesis. Available online: https://www.azonano.com/article.aspx?ArticleID=6181 (accessed on 10 November 2022).
88. Graphene Manufacturing Grup. Aluminium-Ion Battery. Available online: https://graphenemg.com/energy-storage-solutions/aluminum-ion-battery/ (accessed on 10 November 2022).
89. Hazer Group Ltd ASX:HZR. 2021, pp. 1–16. Available online: https://www.ammoniaenergy.org/wp-content/uploads/2021/05/210316-Hazer-Group-LImited-ASX-Small-Caps-Conference-GW-Rev-11.pdf (accessed on 10 November 2022).
90. Williamson, D.; Christie, I. Argonaut Report—Initiation—Cracking the Code. Available online: https://hazergroup.com.au/research-reports/ (accessed on 10 November 2022).

91. Harris, C. Water Corporation Fuelling an Australian-First Hydrogen Project. Available online: https://www.awa.asn.au/resources/latest-news/technology/innovation/water-corporation-fuelling-an-australian-first-hydrogen-project (accessed on 11 November 2022).
92. Alfaro, C.; Rueda, J.; Casallas, Y.; Rodriguez, G.; Malo, J. *Proyecto Investigación Geotérmica de Colombia*; Minenergía: Bogota, Colombia, 2020; pp. 1–172. Available online: https://recordcenter.sgc.gov.co/B22/742_2021EstiPrePotGeotColombia/Documento/Pdf/EstiPrePotenGeoterColom.pdf (accessed on 10 November 2022).
93. Alfaro, C.; Alvarado, I.; Quintero, W.; Hamza, V.; Vargas, C.; Briceño, L. Mapa preliminar de gradientes geotérmicos de Colombia. *Proy. Mapa Geotérmico De Colomb.* **2009**, *34*.
94. Ocean Energy Council. Tidal Energy. Available online: https://www.oceanenergycouncil.com/ocean-energy/tidal-energy/ (accessed on 29 October 2022).
95. Keldie, C. World First: Hydrogen Generated by Tidal Power. Available online: https://maritime-executive.com/article/world-first-hydrogen-generated-by-tidal-power (accessed on 29 October 2022).
96. Osorio, A.F.; Ortega, S.; Arango, S. Assessment of the marine power potential in Colombia. *Renew. Sustain. Energy Rev.* **2016**, *53*, 966–977. [CrossRef]
97. Mit Climate Portal. Why Don't We Use Tidal Power More? Available online: https://climate.mit.edu/ask-mit/why-dont-we-use-tidal-power-more (accessed on 30 October 2022).
98. Paratec. Capacidad Efectiva Por Tipo de Generación. Available online: http://paratec.xm.com.co/paratec/SitePages/generacion.aspx?q=capacidad (accessed on 30 October 2022).
99. IRENA. *Global Hydrogen Trade to Meet the 1.5 °C climate Goal: Part III—Green Hydrogen Cost and Potential*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2022.
100. *Hoja de Ruta del Hidrógeno en Colombia*, 6th ed.; Angewandte Chemie: Hoboken, NJ, USA, 2021; Volume 1, pp. 1–64. Available online: https://www.minenergia.gov.co/documents/5861/Hoja_Ruta_Hidrogeno_Colombia_2810.pdf (accessed on 30 October 2022).
101. IEA. LCOE Range for Selected Dispatchable Low Emissions Electricity Sources in the Sustainable Development Scenario, 2030, 2040 and 2050. Available online: https://www.iea.org/data-and-statistics/charts/lcoe-range-for-selected-dispatchable-low-emissions-electricity-sources-in-the-sustainable-development-scenario-2030-2040-and-2050 (accessed on 9 November 2022).
102. El Colombiano. Made in Medellín: Los Paisas Que Trajeron el Primer Carro Que Funciona con Hidrógeno Verde a Colombia. Available online: https://www.elcolombiano.com/negocios/hevolution-la-empresa-paisa-que-trajo-el-primer-carro-de-hidrogeno-a-colombia-AL18464235 (accessed on 9 November 2022).
103. Gil, M.C. Hevolución Desarrollará Planta Para Producir 1.000 kg de Hidrógeno a Partir de 2023. Available online: https://www.larepublica.co/empresas/hevolucion-desarrollara-planta-para-producir-1-000-kg-de-hidrogeno-a-partir-de-2023-3404792 (accessed on 9 November 2022).
104. Urrego, A. Promigas y Ecopetrol Inauguran Proyecto Piloto Para Generación de Hidrógeno Verde. Available online: https://www.larepublica.co/empresas/promigas-pondra-en-marcha-su-proyecto-piloto-para-generacion-de-hidrogeno-verde-3325410 (accessed on 9 November 2022).
105. Quinchía, A. Ecopetrol y Promigas Arrancaron con los dos Primeros Pilotos de Hidrógeno Verde en Colombia. Available online: https://www.elcolombiano.com/negocios/colombia-pone-en-marcha-dos-pilotos-de-hidrogeno-DJ16974623 (accessed on 10 November 2022).
106. Ecopetrol. El Grupo Ecopetrol Inició la Producción de Hidrógeno Verde en Colombia. Available online: https://www.ecopetrol.com.co/wps/portal/Home/es/noticias/detalle/Noticias+2021/el-grupo-ecopetrol-inicip-la-produccion-de-hidrogeno-verde-en-colombia (accessed on 10 November 2022).
107. Medinilla, M. Ecopetrol Prevé un Electrolizador PEM Piloto de 50 kW Para el 2022. Available online: https://www.energiaestrategica.com/ecopetrol-preve-un-electrolizador-pem-piloto-de-50-kw-para-el-2022/ (accessed on 10 November 2022).
108. Reporte Sostenible. Hub H2 Verde Manizales', el Primer Hub Industrial de Hidrógeno Verde Integrado por Empresas Chilenas y Colombianas. Available online: https://reportesostenible.cl/blog/hub-h2-verde-manizales-el-primer-hub-industrial-de-hidrogeno-verde-integrado-por-empresas-chilenas-y-colombianas/ (accessed on 20 November 2022).
109. Staff, F. Se desarrollará el Primer 'Hub' de Hidrógeno Verde en Colombia. Available online: https://forbes.co/2022/08/30/actualidad/se-desarrollara-el-primer-hub-de-hidrogeno-verde-en-colombia/ (accessed on 20 November 2022).
110. La Unidad de Planeación Minero Energética (UPME). *Plan Energetico Nacional 2020–2030*; Ministerio de Minas y Energía: Bogotá, Colombia, 2019. Available online: https://www1.upme.gov.co/DemandaEnergetica/PEN_documento_para_consulta.pdf (accessed on 20 November 2022).
111. Congreso de Colombia. *Ley 1964 de 2019*; Ministerio de Ambiente y Desarrollo Sostenible: Bogotá, Colombia, 2019.
112. Congreso de Colombia. *Ley 2099 de 2021*; Departamento Administrativo de la Función Pública: Bogotá, Colombia, 2021.
113. Ministerio de Minas y Energías. *Colombia's Hydrogen Roadmap*; Ministerio de Minas y Energías: Bogotá, Colombia, 2021.
114. Consejo Nacional de Política Económica y Social (CONPES). *Política de Transición Energética*; Consejo Nacional de Política Económica y Social (CONPES): Bogotá, Colombia, 2022.