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Article

How to Select Areas for Natural H_2 Exploration? A Case Study in Western Colombia

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Abstract

Although uncertainties regarding natural hydrogen (H_2) reserves remain high, exploration activity is expanding across several countries. To date, the only active production site uses this resource locally for electricity generation; however, operating companies could target industrial markets where H_2 can serve as both an energy source and a chemical feedstock. Surface constraints and proximity to commercial markets will dictate distribution and utilization strategies when alternative options are available. This study introduces a novel tool that integrates surface and subsurface constraints to rank prospective exploration areas, enabling companies to identify opportunities aligned with their specific corporate profiles or business plans. The methodology is applied to western Colombia, a region characterized by many surface constraints and known H_2-generating source rocks; H_2 surface emanations have also been documented. Western Colombia is structurally divided by north–south mountain ranges (Cordilleras) that severely hinder east–west transportation and contribute to regional energy insecurity. Using a comprehensive data compilation, this study demonstrates how applying different weighting schemes to diverse geographical and geological parameters can optimize site selection. The Medellín area ranks highest if the target is the industrial market.

Keywords: natural H_2; Colombia; Cauca Patía; decentralized energy system; Play Fairway Analysis

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1. Introduction

1.1. Low CO_2 Content H_2

The impact of human activity is known to be significant, resulting in environmental damage. In this context, many countries are working to reduce their hydrocarbon (HC) consumption for mobility and heating, as well as industrial applications. For instance, the chemical industry—particularly fertilizer manufacturing—relies heavily on hydrogen derived from natural gas and coal, both characterized by high carbon intensity. Consequently, efforts are accelerating to replace conventional hydrogen (often categorized as gray or black) with low-carbon alternatives. Low-carbon hydrogen can be produced via electrolysis powered by low-carbon electricity (commonly referred to as green or pink H_2) or extracted directly from subsurface geological formations as a natural resource, referred to as natural or white H_2 [1,2]. Hydrogen has attracted considerable interest as an energy

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carrier to buffer intermittent renewable electricity, with electrolyzers and fuel cells receiving significant attention. The industry's interest in the use of H_2 has grown, and H_2 consumption has increased. However, the production of green H_2 has not kept pace, and the search for other sources of low-carbon-content H_2 has accelerated [3]. Methane pyrolysis [4] or mine slag treatments [5] and the exploitation of naturally occurring hydrogen generated within the Earth [6] are alternative pathways for producing low-carbon hydrogen. The emerging natural H_2 exploration industry has developed within this context.

Natural H_2 emissions have been known for decades, but their potential as a commercially exploitable resource received little attention until recently [6–8]. As recently as 2022, many people still stated that free H_2 did not exist on Earth, even though at that time, Mali had already been producing it for eight years [9,10]. Today, its existence is no longer disputed, but the quantities that could be produced economically remain a matter of debate [2,11–13]. In other words, the resources are recognized, but the reserves remain to be proven [14].

In the HC industry, the transition from resources to reserves is associated with a reduction of one or two orders of magnitude. As a reminder, resources refer to quantities generated within a basin in a given area, whereas reserves refer to accumulations identified in a known reservoir and which can be produced economically. In Mali, currently the only country where natural H_2 is produced, the small production, about 1500 m^3/day, is used to generate electricity for a local town [15]. The gas is directly burned in a gas turbine to generate this electricity, resulting in no transportation, purification or storage costs. At the other end of the H_2 market spectrum, some stakeholders envision long-distance maritime transport to supply overseas industrial hubs [16,17]. To date, a pilot project for H_2 maritime transport between Australia and Japan has been conducted, but large-scale commercial development remains stalled by poor economic viability. Research is, of course, actively underway to reduce these costs. Regardless of the cost and feasibility of H_2 transport, most studies suggest that natural H_2 could be produced at low cost, potentially undercutting gray or black hydrogen, depending on key production variables, particularly flow rate and field depletion timelines [13,18].

1.2. Choosing Natural H_2 Exploration Acreage

Production costs (both OPEX and CAPEX) vary drastically depending on the target end-use: off-grid local utilization without purification contrasts sharply with long-distance supply to clients requiring high-purity H_2. Operating companies must weigh these trade-offs when defining their exploration targets. The size of the company also has a significant impact on its decisions; in the hydrocarbon sector, major energy companies typically target "elephants" (e.g., field sizes exceeding 500 million barrels), whereas independent operators target smaller, niche accumulations. In natural H_2 exploration, the current number of discoveries remains insufficient to identify the location of very large deposits, but we can already consider the issue in terms of probability and market potential.

Policymakers, particularly those seeking to promote the development of this industry in their countries, are also grappling with the question of how to utilize this resource. Priorities vary between ensuring energy self-sufficiency and optimizing national trade balance and having more to export [19]. Depending on economic maturity, energy insecurity—defined as the lack of affordable energy available 24 h a day—in certain areas can be a significant factor, whereas in others, the national shortage of other energy resources is the key issue. Geopolitical volatility and domestic electoral cycles further reorder these policy priorities. For example, in France, priority has been primarily placed on regions that have helped the H_2 industry take root over the past five years, hence the focus on Nouvelle-Aquitaine and the East (Moselle and Lorraine) [20]. Conversely, in Colombia

(Figure 1), the central government of G. Petro directed public funds in 2024 for initial exploration work toward the west of the country—which has no HC deposits—and the northern La Guajira region. The latter hosts a large coal mine and is close to offshore gas fields, yet it suffers from severe energy insecurity.

Figure 1. Study area and grid resolution of the Play Fairway Analysis. All maps starting with Figure 6 correspond to the red rectangle; the scale will not be repeated, nor will north always be shown vertically. The locations of the three major cities—from north to south, Medellín, Bogotá, and Cali—will be indicated by polygons.

National energy mixes, consumption profiles, and policy priorities vary widely, leading to divergent strategic choices for project developers and industrial operators. The purpose of this study is not to advocate for specific policy pathways, but rather to provide tools that enable informed decision-making in an uncertain world. Hydrogen is not easy to transport because the necessary infrastructure is not yet in place, and is unlikely to change until the circulating volumes reach a critical mass. Natural gas benefits from millions of kilometers of pipelines and, moreover, can be liquefied fairly easily for transport via shipping. Consequently, early-stage deployment strategies for H_2 prioritize near-source commercialization. However, this still leaves considerable room for maneuvering and, consequently, important decisions to be made. A fundamental question is whether to prioritize localized supply chains—suited for direct energy applications—or target industrial sectors utilizing H_2 as a chemical feedstock.

The market has its reasons. . . but so does geology. At present, H_2 E&P (Exploration and Production) remains in its infancy, and there remains a great deal of uncertainty. Prior drilling, geoscientists assess plays with POS—probabilities of success. However, POS evaluation is a structured risk-quantification process rather than a speculative gamble.

Tools for managing this uncertainty do exist in the oil and gas industry, but they are very expensive and tailored to the specific data needs of that sector: 3D imaging for subsurface data and, for surface data, a global market with a set price per barrel. While it is true that this price fluctuates and that political risks exist, the industry has been dealing with these factors for over 100 years.

New tools are currently being developed, tailored to this emerging industry and its constraints, and this article presents a specific application centered on western Colombia (Figure 1), performed with the prototype of geoscience software EarthSight^{TM}. This region exhibits diverse terrain and highly variable population densities, with the electricity and gas distribution networks covering only a portion of the territory. Underground, certain rocks with H_2 generation potential are present but discontinuously distributed. Following the assessment of surface constraints and subsurface resource favorability, this study demonstrates how a balanced risk–opportunity framework optimizes strategic decision-making. Specifically, we illustrate how to select exploration zones based on whether the strategic objective is to alleviate regional energy poverty or to produce H_2 as a feedstock for industrial consumers. While the baseline dataset remains identical across scenarios, parameter weighting varies according to the prioritized objective. To evaluate these distinct pathways, we modeled two contrasting baseline scenarios: energy insecurity (Scenario A) and industrial market (Scenario B).

2. Methodology and Basic Concept

2.1. Methodology

The Play Fairway Analysis (PFA) method (Figure 2) is applied to establish a regional favorability map. Rather than providing an exhaustive or strictly predictive representation of the actual resource potential, this map serves as a rapid decision-making tool. Its primary purpose is to screen and prioritize areas where further exploration campaigns could be deployed or, conversely, ruled out.

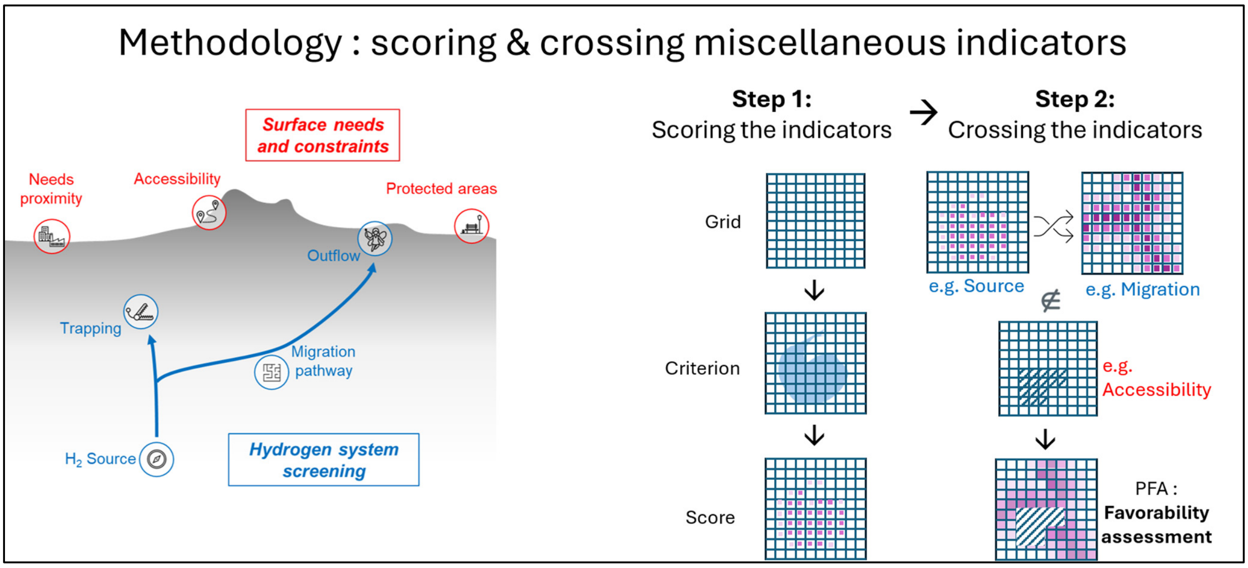

Figure 2. Conceptual workflow of the Play Fairway Analysis (PFA) methodology applied to natural hydrogen exploration.

The initial phase involves defining and collecting publicly available data across a set of relevant criteria to identify:

- Surface constraints that may restrict or facilitate exploration activities;
- Local community and industrial demands;

- Subsurface conditions favoring H_2 generation and migration;
- Surface H_2 seepage indicators.

These datasets are subsequently processed and analyzed to generate normalized favorability grids, which are then utilized to produce a potential heatmap for each individual parameter. The attribution of weight to the individual PFA criteria is adaptable and varies depending on the specific hypotheses.

Finally, the thematic overlay and combination of these maps yield three core outputs:

- A surface constraint and demand map;
- Exclusion zones for H_2 exploration;
- A subsurface H_2 presence favorability map, highlighting sectors likely to host significant hydrogen concentrations.

The final deliverable is a comprehensive synthesis map integrating all surface and subsurface parameters. This synthesis provides a first-pass exploration framework, identifying areas that are more or less favorable for natural hydrogen exploration and future exploitation based on the selected criteria.

The PFA presented in this study focuses exclusively on western Colombia, an area that could be of interest to operators if exploration begins, but which presents numerous challenges due to its geography. The eastern region of this country was omitted from the analysis due to its existing extensive electricity supply from hydrocarbon operations and the sparse population density of its Amazonian sector. The study area, the onshore portion of the red rectangle in Figure 1, was discretized into 3559 cells of approximately 100 km^2 each, covering a total area of roughly 355,900 km^2. This spatial resolution was selected to prevent data overinterpretation and to ensure that the granularity of the favorability mapping remains consistent with the precision of the input parameters.

2.2. Natural Hydrogen

H_2 is continuously generated in the subsurface by various processes [21]. Following the classification in four generating rock types [22], H_2_GR1 is the oceanic lithospheres that can be oxidized upon contact with water [23], H_2_GR2 is the sedimentary and intrusive rocks that are also iron-rich and that may reduce the water [24], H_2_GR3 comprises the radioactive rich rocks that can split water molecules [25], and H_2_GR4 is organic-rich source rocks that may also generate H_2 at high temperatures after having generated oil and gas [26]. Many other researchers have not only worked on these generating rocks but also, now, more globally, on the H_2 system, including expulsion, migration, accumulation and dismigration up to the surface [27,28]. The transport of H_2 from the generating rocks to the reservoirs may take place through faults in the case of very tight rocks nearby. Conversely, in sedimentary basins, the transport predominantly occurs through regional carrier beds via advective flow, either as a free-gas phase or dissolved in aqueous fluids [29,30]. For three of the GRs, water is necessary for H_2 generation, but it also influences the transport; the presence of dynamic water recharge is therefore key for H_2 systems [31]. After H_2 generation, since H_2 solubility in water is higher at greater depths [32], aquifers are used as one of the carrier beds and are the major ones in a sedimentary context [27]. The analysis presented here is based on a weighting of the data, not on a physical model of the phenomena. The probability of water recharge through precipitation and topography, as well as its flow through faults, will be taken into account; however, the exact flow within the aquifers and the rate of that flow will not be considered. This type of work, although highly relevant, must be carried out at a more advanced stage of exploration and on a more local scale.

3. Case Study Data

3.1. Western Colombia Surface Constraints

Western Colombia, extending from the Central Cordillera to the Pacific Coast, is divided by two major north–south-trending mountain ranges: the Western and Central Cordilleras, which reach elevations of approximately 4000 m and 5000 m, respectively. The mountain ranges strongly influence regional geography and isolate the Cauca Valley, located between the two cordilleras, from the Magdalena Valley to the east (Figure 3). The Cauca and Magdalena Rivers, the two principal river systems in the region, both flow predominantly from south to north. The Central Cordillera hosts several major volcanic zones, particularly south of the slab tear that separates the flat-subduction segment to the north from the steeper subduction regime to the south [23]. Overall, both the mountainous regions and the Pacific coastal area are sparsely populated, whereas major cities like Bogotá, Cali and Medellín are located within the intermontane valleys.

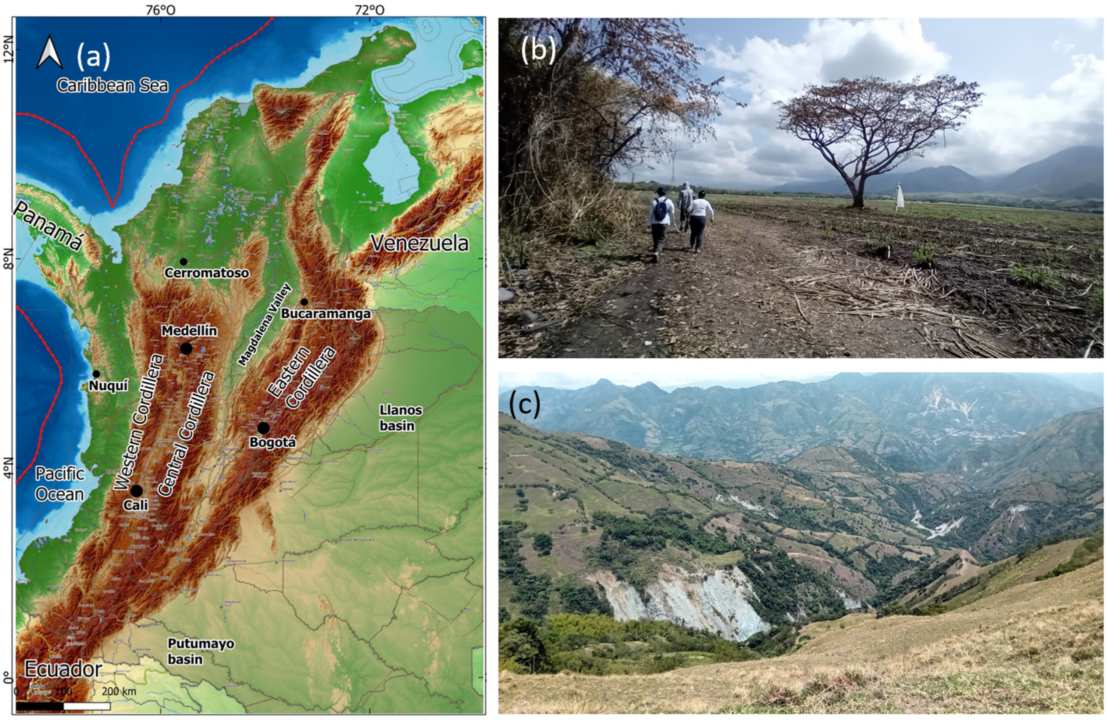

Figure 3. (**a**) Topography of Colombia showing the cordilleras and the main rivers. The color-coded map shows elevation ranging from 0 (green) to 5700 m (brown). The red lines highlight the two subductions (**b**) Example of the landscape in the Cauca Valley between the Western and Central Cordillera. (**c**) Landscape in the Central Cordillera.

3.1.1. Topography

The terrain in western Colombia is very rugged, and road infrastructure is limited outside the valleys. The major rivers flow from south to north and ultimately discharge into the Caribbean Sea. Only one major road crosses the Western Cordillera and leads to the port of Buenaventura (Figure 1). Many of the smaller towns and villages along the Pacific Coast are accessible only by small plane. In contrast, approximately ten east–west roads cross the Central Cordillera, connecting the Cauca and Magdalena Valleys along a north–south corridor approximately 800 km long. The capital, Bogotá, is located in the eastern part of the Magdalena Valley, at an altitude of 2800 m, on the edge of the Eastern Cordillera (Figures 1 and 3), whereas Cali (1000 m) and Medellín (1500 m) are located in the Cauca Valley. There are virtually no trains in Colombia, and long-distance travel is mainly by plane. The main road maps and the distance to the roads are incorporated within the PFA.

3.1.2. National Parks

Colombia encompasses approximately 65 national parks, where industrial and extractive activities are prohibited. Collectively, these protected areas span more than 10% of the country's land area. Although the largest parks are located eastward in the Amazon Basin, several protected zones intersect the Andean Cordilleras, notably surrounding major volcanic complexes (Puracé, Los Nevados, and Nevado del Huila). Accordingly, these zones are excluded from the acreage evaluated for natural H_2 exploration. The country also includes so-called indigenous territories, where the rules may differ, but local authorities have not yet established a formal stance on natural H_2 development. Energy-related industrial projects, such as dams or wind farms, are being developed in these territories following agreements with the local residents. Consequently, these areas were retained in the analysis, as interest in potential H_2 projects is expected to be evaluated on a case-by-case basis.

3.1.3. Other Excluded Areas

As an established oil and gas (O&G) country, Colombia maintains an extensive registry of existing exploration licenses, mapped publicly via the Agencia Nacional de Hidrocarburos (ANH) portal. (www.anh.gov.co). Under the new legislation currently under discussion, incumbent O&G operators are expected to be granted exploration of this new resource within their licenses; however, it will not be accessible to new entrants (NE in the scenario). The O&G licenses will therefore be excluded from the open-acreage screening analysis. Regarding the mining sector, the regulatory framework is more ambiguous, as the draft legislation does not explicitly grant mining entities rights to subsurface fluids. Rather than treating mining concessions as exclusion zones for H_2 exploration, their high energy intensity positions them as prime candidate off-takers.

3.1.4. Electricity Power Grid

Colombian electricity is highly decarbonized, with hydroelectricity supplying approximately 75% of national demand on average. The remaining share is produced from hydrocarbons and coal. However, this generation mix fluctuates significantly during El Niño Southern Oscillation cycles. Figure 4a highlights the power transport grid (*Sistema Interconectado Nacional (SIN)*). Of note is the connection with the oil fields in the east, in the Llanos Basin, and the gas fields in the north, including offshore, as well as the Magdalena Valley corridor, which hosts major hydropower plants. It is worth noting the absence of power transmission in the west and across large areas of the plains to the east, as well as in the north, outside the Caribbean coast (Figure 4a). Off-grid remote areas (*Zonas No Interconectadas*) rely primarily on localized diesel generation or small-scale run-of-river hydro schemes.

3.1.5. Hydrocarbon Distribution

The large majority of the oil production in Colombia takes place in the Andes foreland [33–35], named the Llanos Basin, in the eastern flat area of the country (Figures 3 and 4). Pipelines transport this oil toward the capital, Bogotá, and to the refineries on the Caribbean coast, from where it can be exported (Figure 4). In contrast, the gas is mainly produced in the north, offshore in part, and the natural gas pipelines allow transport to the south and the major cities (Bogotá, Medellín, and Cali). Part of the gas is also now coming from the former large oil fields of Cusiana and Cupiagua in the Eastern Cordillera foothills, which are now almost oil-depleted [36]. Figure 4b clearly shows that a large part of the country is not connected. In that case, the gas is distributed in propane tanks, often by road but sometimes even by cart or on the back of donkeys. As a result, the farther away you are from distribution centers, the more expensive the gas is. These most isolated consumers are also often the poorest.

Due to this geography and the spatial concentration of energy production facilities, broad expanses of the country lack direct energy grid access. They are not the most populous regions, but are often the poorest. Local energy sources—such as solar panels, small wind turbines and small hydroelectric systems—are therefore important. Within this context, natural hydrogen offers a compelling decentralized power solution, paralleling the off-grid power model demonstrated in Mali.

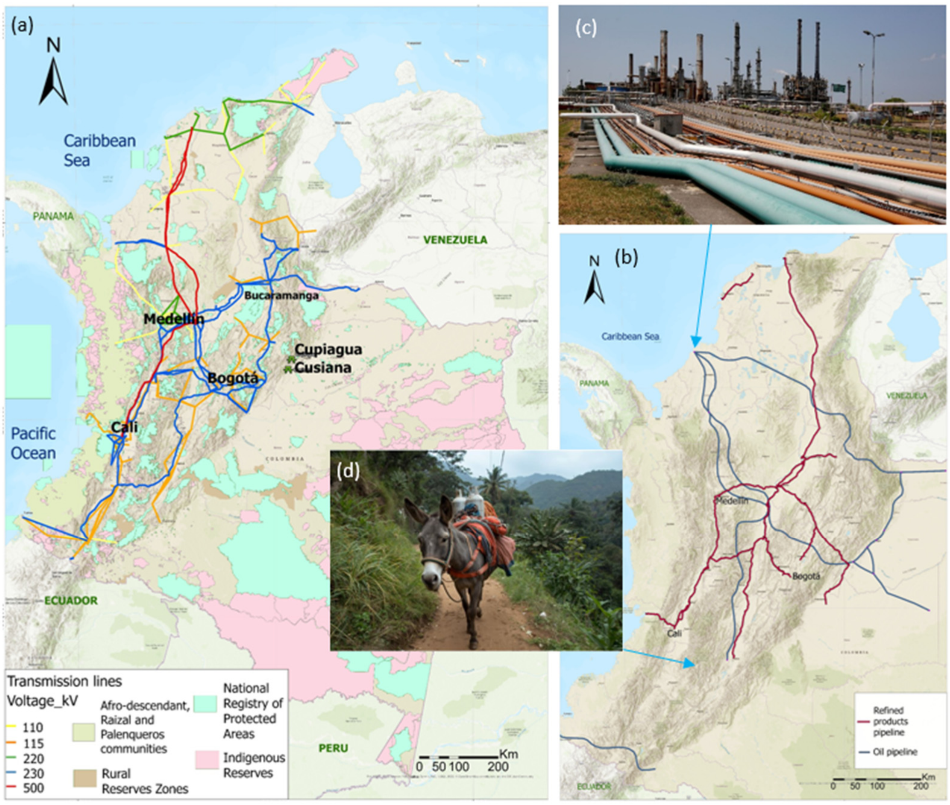

Figure 4. Surface constraints: (**a**) Protected areas (light green and ochre), indigenous territories (in pink) and electricity transport grid. (**b**) Oil and gas distribution; large pipelines connect the production zone to the refineries. (**c**) Caribbean coast refineries. (**d**) Last-kilometer transport mode in the Cordilleras.

3.2. Subsurface Constraints: H_2 Potential in the Study Area

Data regarding natural H_2 potential are starting to be published in Colombia, although industrial exploration has not started yet. The potential H_2_GR has been mapped, and H_2 content in the soil has been measured by various Colombian groups, including the Geological Survey of Colombia (SGC), the National University (Bogotá and Medellín branch), the National Hydrocarbon Agency (ANH) and the national oil company Ecopetrol [37]. The presence of H_2 within the HC exploration wells has also been reported by Ecopetrol [38]. The University of Pau (UPPA) has also published data [39,40], and the monitoring of various gases, including H_2, in the Central Cordillera has been carried out by the Nacional University of Bogota [41].

3.2.1. Presence of H_2_GR

The maps used in this study were published by N.A. Carrillo-Ramirez for the western part of the country. Readers may refer to the cited bibliography for the geology of Colombia and to access the data for H_2 in the western part of the country [39–41]. Regarding the potential of the Colombian coal to generate H_2, data has been published by [42]. The western part of Colombia, from the Central Cordillera to the coast, consists mainly of accreted oceanic lithosphere [43,44]. Mafic and ultramafic rocks (H_2_GR1), Mesozoic in age, are present [45]. Although the degree of serpentinization, and consequently, the remaining H_2 potential, varies at all scales, rock presence was retained as the primary criterion for this regional-scale analysis [39]. Granitic intrusions have been noted and represent potential H_2_GR2 and H_2_GR3. Tertiary coals (H_2_GR4) are present in the sedimentary cover. Exploitation took place near the surface and mainly in open pits; the probability of having rich organic matter deeply buried from the Central Cordillera toward the west is very low since the basins are not deep enough. However, in the Magdalena Valley this could be possible [46].

3.2.2. H_2 Emanations in Western Colombia

Various groups have already measured and mapped the H_2 content in the soil in Colombia: Ecopetrol for the Llanos and Putumayo foreland basins [37] and the universities for the western part of the country [39–41]. For western Colombia, the synthesis of these data has been done and published by [39]; published maps (Figure 5b) will be used for the PFA. All data from the western region of Colombia examined here were collected near the surface (less than one meter) using the standard soil gas sampling method, with GA5000-type sensors [39,40]. The limitations of this type of one-time measurement without monitoring are real and relatively well known [22,47]. Soil moisture, soil type, microorganism content, and barometric pressure all influence the measured values [48,49]. Only the measurements taken by Ecopetrol in the oil-producing area were collected from wells; these are not used in this study [38]. The exact values of the soil's H_2 content (in %) should never be considered a constant figure representative of an area; only long-term monitoring can quantify a flux. Conversely, any value higher than the concentration of H_2 in the air (0.5 ppm) indicates H_2 generation, either in the soil or at depth. Microorganisms usually consume H_2 [50] and thus reduce the values measured at the surface. There is a wealth of literature on the subject, which need not be discussed here since these surface indicators will be used only to confirm the existence of H_2 leaks in western Colombia.

The existence of known emissions is linked to the occurrence of measurements; while it is possible to assign a positive weight to areas where emissions are known, areas without measurements cannot be penalized in the screening matrix. Published data (Figure 5b) show emanations near the Cerro Matoso mines in the north, along the border of the Central Cordillera southeast of Medellín, and around Cali. Consequently, these surface manifestation datasets served primarily as a calibration layer to validate the presence of an active H_2 system.

3.2.3. Reservoir, Traps and Seal

The presence of H_2 accumulations critically depends on the presence of a structural reservoir and a cap rock. While there is little doubt about the existence of folds—and thus structural traps—in this compression zone, the existence of an effective cap rock for an H_2 reservoir remains speculative. The study area is large, and it is not feasible to identify a structure to drill at this scale. While we are fully aware of the fundamental role of these components of the H_2 system, detailed trap and seal characterization falls outside the scope of this regional screening. A pragmatic initial assumption—likely to be adopted by early-mover operators—is that prospective reservoirs correlate with thick sedimentary sequences, favoring intermontane valleys. New data will need to be acquired to clarify these factors in areas where permits are granted, once regulations allow it.

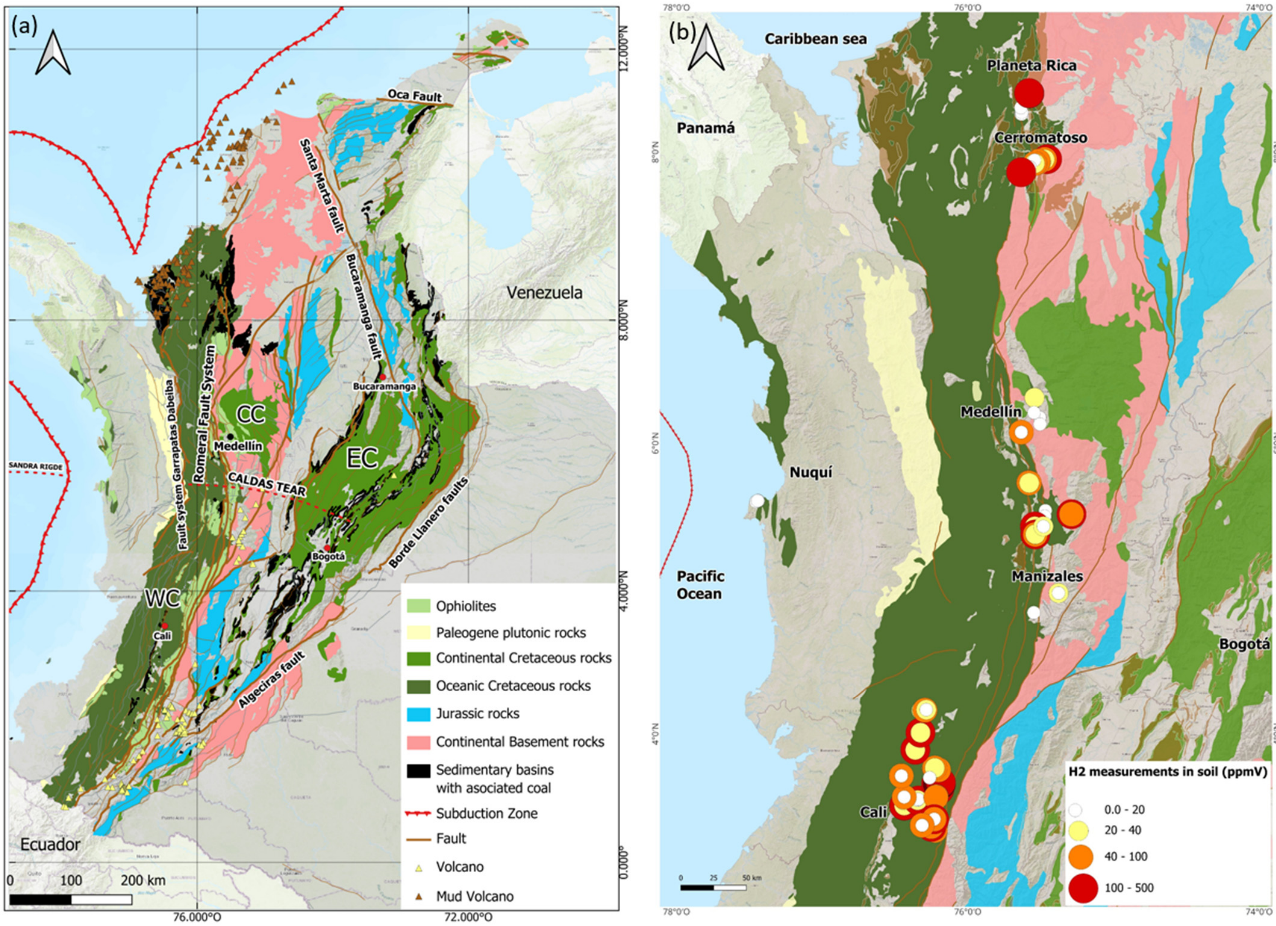

Figure 5. Geology of Colombia. (**a**) Main terranes. (**b**) H_2 emanations in the soil of western Colombia (both modified from Carrillo et al. 2025 [39]). The emanation maps show that data were collected—or published—for only three areas. Therefore, they cannot be used directly to create favorability maps, but they will be used for quality control.

4. Results

Play Fairway Analysis (PFA) enables the evaluation of diverse exploration scenarios, leveraging Colombia's rich spatial and geological datasets to generate multi-layered prospective maps. The weight assigned to each criterion may vary depending on the objectives. To illustrate potential applications of this framework, two contrasting scenarios are presented: Scenario A aims to use H_2 locally to combat energy poverty, while Scenario B targets commercial supply to industrial end-users. While baseline criteria—such as infrastructure proximity—remain constant, their weighting polarities invert depending on the scenario goal. For example, if an area is connected to the national power grid, the benefits of local electricity production from H_2 are not as strong. Conversely, if the area is not connected and relies solely on diesel generators, it will be considered a positive factor for Scenario A. Conversely, absolute exclusion zones (e.g., national parks) retain identical zero-favorability weights across both scenarios.

All maps are presented within the same area, which is shown in Figure 1. To make the maps easier to read, the locations of the three major cities—Medellín in the north, Bogotá in the east, and Cali in the south—have been marked on the final maps as small polygons. The names are not repeated because there is no ambiguity. The southeastern part of the map corresponds to the Putumayo Basin. The geological setting there is very different from that of the west, and the various geological formations, which do not outcrop, have not yet been thoroughly studied. This part of the maps has not been calibrated with respect to geological features such as H_2_GR presence.

4.1. Maps of the Surface Constraints

The model incorporates six primary surface parameters to evaluate regional accessibility and energy requirements (Figure 6). Each criterion is computed from public datasets available from governmental websites, using Python scripts to define the heatmaps and their scoring.

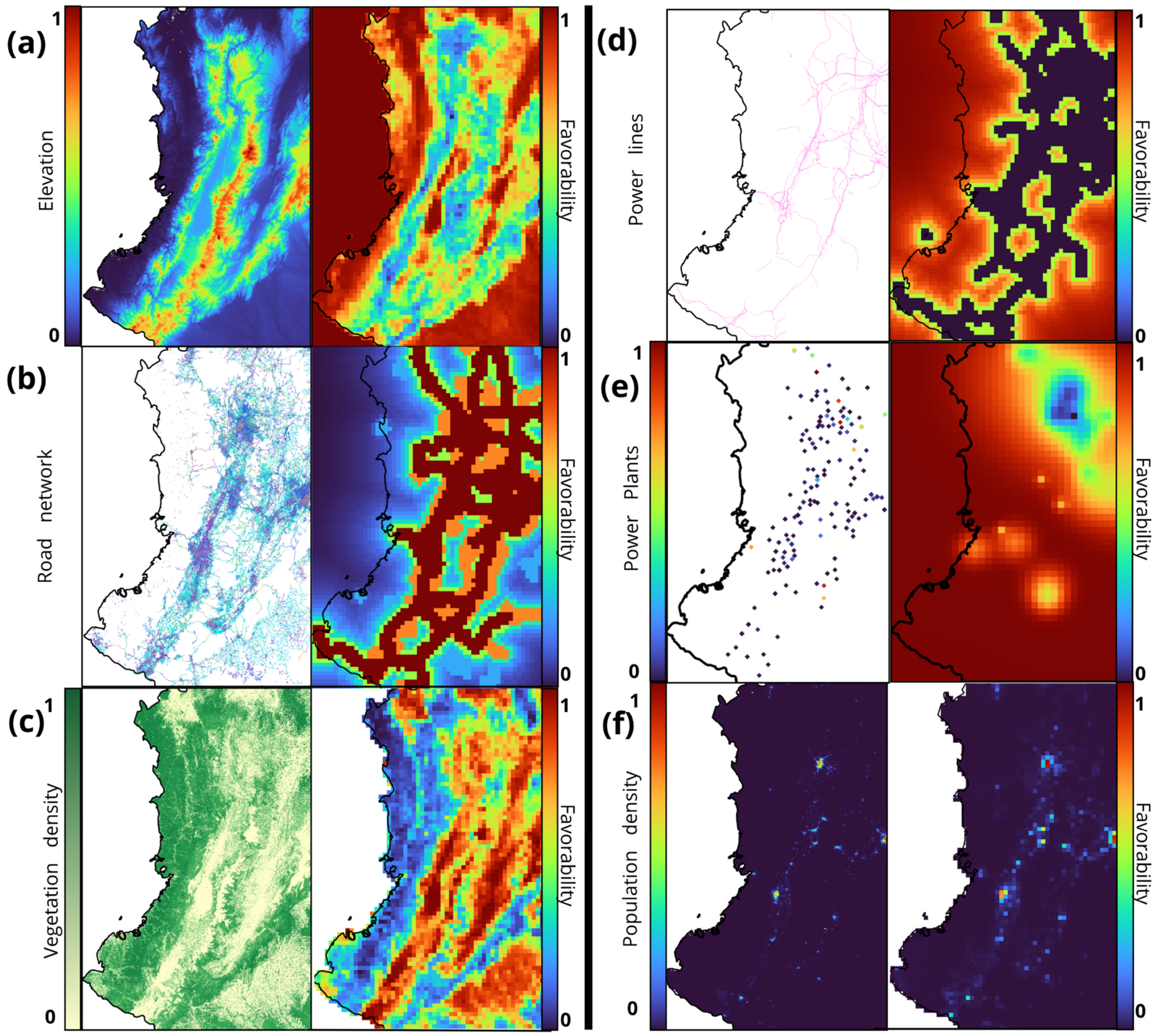

Figure 6. Favorability maps of the surface constraints; see location of the studied area in Figure 1. For each criterion, the map of the data used is displayed to the left of the favorability criterion. Positive factors are highlighted in red, whereas negative ones are presented in blue. (**a**) Elevation: The high reliefs are weighted negatively and appear in blue. (**b**) Existence of roads: Areas lacking infrastructure or with poor accessibility were designated as low favorability, represented by blue. (**c**) Density of vegetation: The least densely vegetated areas, which are considered more accessible, were assigned the highest scores. For Scenario A, the final aim is a reduction in energy insecurity. (**d**) Existence of the electricity distribution grid, which in this case is ranked negatively. (**e**) Existence of power plants, mainly hydroelectric in this region. (**f**) Density of population: Large cities such as Medellín or Cali have been capped at 7000 inhabitants to better visualize the small ones.

High relief and steep slopes introduce severe logistical constraints; consequently, elevated areas analyzed using the Digital Elevation Model (DEM) of Colombia are weighted negatively (Figure 6a). To support field exploration, areas with steep slopes and difficult terrain were analyzed using the same DEM to compute point-by-point slope values. A threshold of 30°, representing the limit of practicability, was applied to isolate steep terrain. The proportion of steep slopes per cell was then calculated to produce a heatmap for this parameter. Lastly, the map was inverted and normalized to attribute maximum favorability scores to topographically unconstrained zones (Figure 6a). Regions lacking infrastructure or characterized by poor accessibility are designated as low-favorability zones. To model this accurately, the distance-to-roads criterion follows a hyperbolic decay function combined with a specific road weight. If a road intersects a grid cell of the PFA, that cell receives the maximum favorability score, with major infrastructure like highways starting with a higher base score than minor roads. For cells lacking direct road intersection, the score decreases stepwise (1/2, 1/3, 1/4, etc.) based on the cell distance from the nearest road. This mathematical decay ensures that immediate roadside areas maintain high favorability, while remote zones drop rapidly into low-favorability thresholds (Figure 6b). Densely forested or vegetated zones restrict physical access and project development. Therefore, the least densely vegetated areas are considered the most accessible and are assigned the highest favorability scores (Figure 6c). The proximity to the existing electricity network is computed using the same algorithm as the roads criteria and weighted in the baseline needs assessment (negatively for Scenario A; Figure 6d). The locations of regional power generation facilities, primarily hydroelectric plants, are mapped to identify areas with established energy production (negatively for Scenario A; Figure 6e). Demographic concentrations highlight where energy demand is localized (Figure 6f). To prevent extreme demographic clusters from skewing the spatial visualization, population data for major urban centers (such as Medellín and Cali) were capped at a threshold of 7000 inhabitants per cell. This capping ensures that smaller municipalities and rural communities remain clearly visible and distinguishable in the analysis.

The six surface parameters—population density, electricity grid, road networks, relief, power plants, and vegetation density—were dynamically re-weighted to produce two distinct favorability maps tailored to the strategic objectives of each scenario (Table 1).

Table 1. Weight per scenario for surface constraints. These values are user-specified and can be adjusted. They describe the parameters used to define the maps in Figure 7.

Parameter	SCENARIO A	SCENARIO B
Elevations/relief	0.5	0.5
Distance to major roads	0.6	0.5
Vegetation density	0.3	0.3
Distance to the distribution grid	(negative impact) 0.7	(positive impact) 0.7
Distance to power plants	(negative impact) 0.3	(positive impact) 0.3
Population density	0.9	0.7
Restricted zones (total exclusion)	1	1

Scenario A (off-grid energy poverty relief) focuses on underserved populations requiring decentralized energy solutions. To prioritize communities in need, population density is assigned the highest weighting factor (0.9). Crucially, the influence of electricity grids (0.7) and power plants (0.3) is set to a negative impact, penalizing proximity to existing power infrastructure to isolate remote, unelectrified regions. Conversely, Scenario B (industrial market integration) models a market-oriented framework where natural H_2 is evaluated as a commercial commodity, such as an industrial fuel or chemical feedstock for fertilizer production. In this case, the impact directionality for power plants and grid infrastructure is reversed to positive: favorability increases with proximity to existing energy assets, reflecting the spatial distribution of industrial consumers and commercial off-takers.

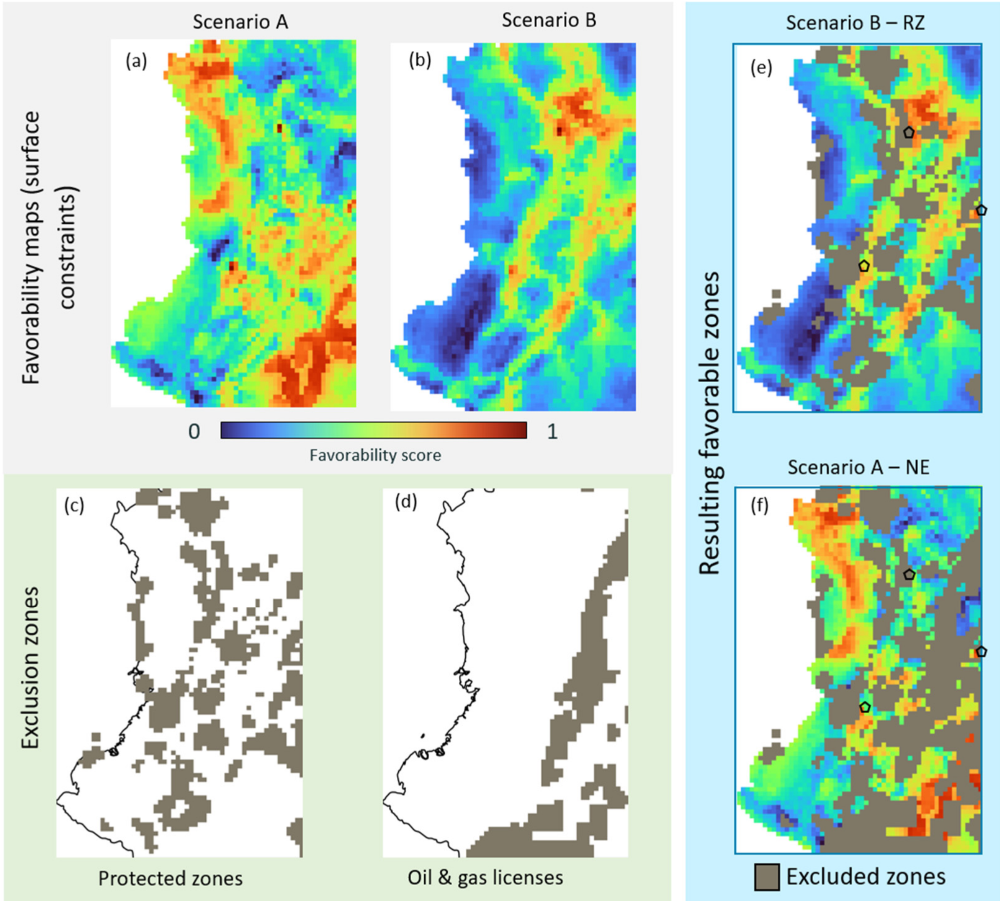

Figure 7. Maps of areas where H_2 exploration can be conducted, considering land-use constraints and objectives. The weight given to the constraints is summarized in Table 1. Scenario A: Local use of H_2 to combat energy poverty. Scenario B: Industrial use. In Scenario B-RZ, the exclusion zones are only the national parks, whereas in Scenario A-NE (for new entrants), the oil and gas zones are also excluded. (**a**) Surface constraint based on Scenario A; the more favorable zones are the remote ones. (**b**) Scenario B, targets an industrial market, with the best zones surrounding Medellín. (**c**) Exclusion zone corresponding to the national park. The offshore one is Gorgona Island. (**d**) Existing licenses for O&G prospection. (**e**) Favorable zone for an industrial market, either interested in working with oil companies or an oil company with assets in the Magdalena Valley or the foreland. (**f**) Favorable zone for new entrants to fight against energy poverty.

A comparison between Figure 7e,f emphasizes the differences between the areas that should be prioritized based on the objectives. This highlights the need to consider market factors in decision-making.

4.2. H_2 System

As explained earlier, the lack of information on reservoirs and caps currently prevents us from taking into account all the factors necessary for H_2 accumulation; therefore, we are limiting our analysis to the presence of generating rocks and faults that allow water to infiltrate the terrain and then circulate. This is a first step to eliminate areas with low potential right from the start.

4.2.1. Favorability Maps of the H_2 Presence

H_2-generating rocks found in Colombia, and listed above, include the mafic and ultramafic rocks of the accreted oceanic lithosphere (H_2_GR1), iron-rich facies and intrusions (H_2_GR2), radioactive facies (H_2_GR3), and coal deposits (H_2_GR4). Although radiogenic facies remain poorly characterized in the study area, the lower continental crust is hypothesized to contain radiogenic elements. The ranking of the zones performed here does not model the burial, the temperature evolution or the kinetics of the reactions, respectively, with the oxidoreduction, radiolysis or thermal maturation of the organic matter. Consequently, in the absence of quantitative kinetic constraints for each pathway, equal weights were assigned to all four H_2_GR categories to establish a neutral baseline and avoid a priori bias toward any specific generation mechanism. The presence of these H_2_GR units was mapped spatially (Figure 8), with tertiary coal deposits (H_2_GR4) treated as a binary variable indicating presence (favorability = 1) or absence (favorability = 0) (Figure 8d).

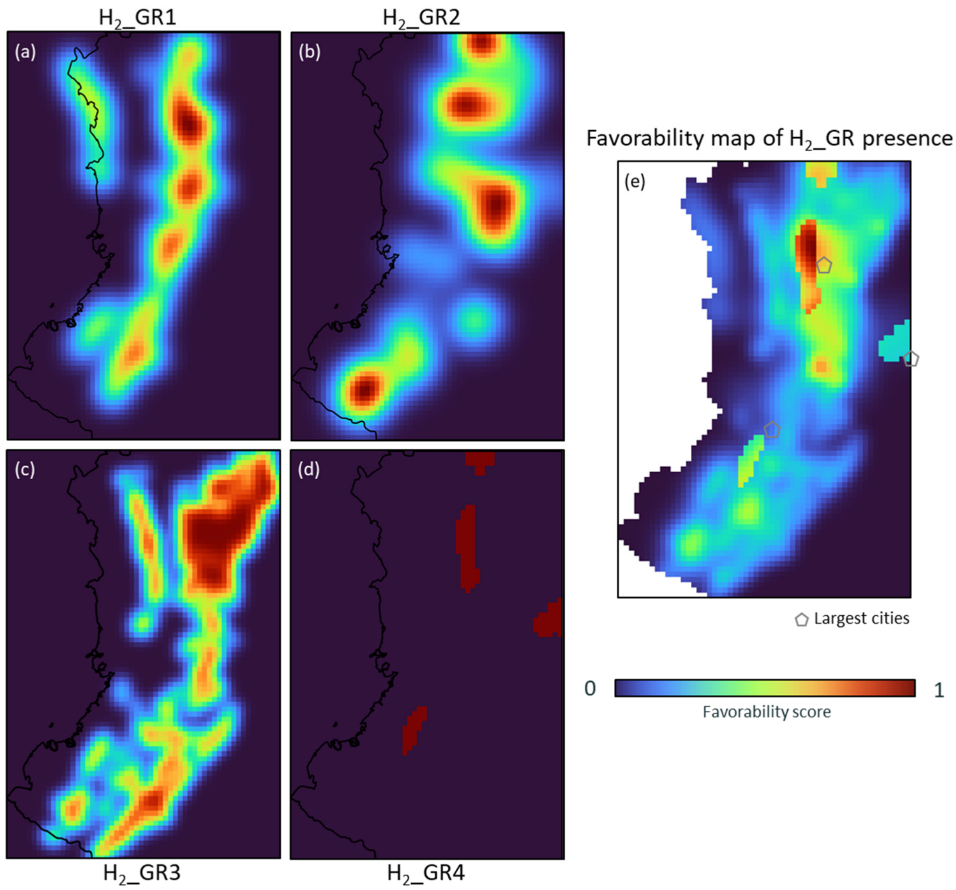

Figure 8. Maps of generating rock favorability based on the presence of the potential generating rock. (**a**) H_2_GR1: Mafic and ultramafic; the basalt near the coast is weighted with a lower potential than the mantle rocks in the cordilleras. (**b**) Mineral deposits and intrusion. (**c**) Potential radioactive lower crust. (**d**) Coal deposit in the Tertiary sedimentary cover. (**e**) Resulting variability for H_2 generation in the studied area. Gray pentagons represent the largest cities.

4.2.2. Favorability Maps of Water and H_2 Migration Pathways Based on Fault Presence

Except for the H_2_GR4, natural H_2 generation processes depend heavily on the presence of water. Once generated, hydrogen—which is soluble in water at great depths [32]—can migrate as a dissolved gas or as a free gas phase [27]. If dissolved, H_2 will follow the same paths as water. In sedimentary environments, porous rocks—known as aquifers or carrier beds—play the primary role in fluid migration. However, in the case of low-permeability rocks, fault and fracture networks become the dominant factor. Full-scale dynamic modeling of multiphase fluid circulation across a vast, structurally complex region exceeds the scope of a regional PFA. Instead, regional fault density was adopted as a first-order proxy for fluid migration favorability and meteoric water recharge (Figure 9). It is acknowledged, however, that fault behavior is complex and non-binary: depending on stress regime, spatial orientation, mineralization, displacement, and connectivity, faults can function as high-permeability conduits, impermeable seals, or leaking pathways. While high fault density is assumed here to correlate with enhanced structural permeability and fluid connectivity at a screening scale, dense faulting also increases the risk of structural breaching and gas dissipation rather than subsurface entrapment. This first-order monotonic approximation serves as a regional baseline; detailed local-scale evaluations must incorporate fault-seal mechanics, stress analysis, and trap integrity. To validate this regional migration model, proxy indicators of natural hydrogen presence were integrated. Specifically, geochemical field data on surface gas seepages from Carrillo-Ramirez (Figure 5b) [39,40] were utilized to cross-validate the favorability mapping.

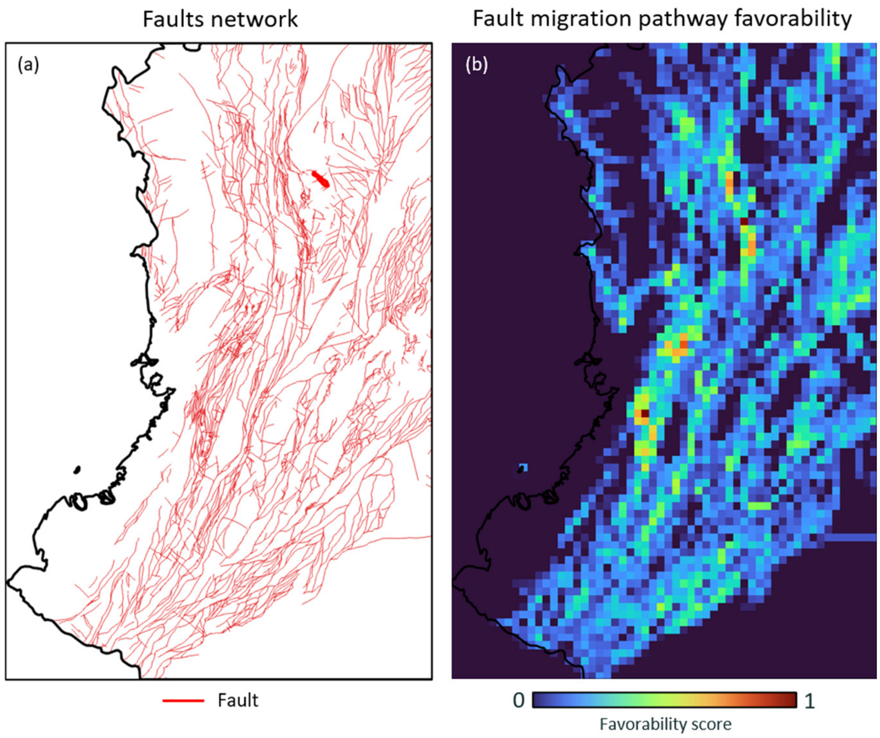

Figure 9. Fault migration pathway. (**a**) Fault network, in red, and (**b**) resulting favorability map.

4.2.3. Subsurface Constraints and Favorability of H_2 Presence

The maps of the various H_2_GR areas (Figure 8) and the fault network (Figure 9) are combined to produce the favorability map shown in Figure 10. Subsurface hydrogen transport was simulated using Dijkstra's algorithm over an eight-neighbor grid, starting with source cells with generation values > 0.65. Then, the spatial probability of hydrogen presence along the computed minimum-cost paths was calculated using an exponential decay model.

This map identifies the area with the greatest potential between the Cali (south) and Planeta Rica (north) zones. Medellín is roughly at the center of the zone. This is mainly due to the presence of various potential H_2_GR in the area. Topography and fault network facilitate fluid circulation and its infiltration to deep levels. It should be emphasized that this analysis is purely cartographic and does not constitute a dynamic model of water transport or H_2 generation and migration between the mountain ranges and the valleys. Such modeling must be conducted at a finer spatial scale, incorporating subsurface geometry, porosity, permeability, H_2 generation kinetics, and other parameters beyond the scope of this PFA. The large-scale computation of the favorability of H_2 presence in the subsurface presented here serves primarily to eliminate non-prospective areas. A map with lower resolution is presented in Figure 10b. The areas of greatest interest, based on current data, are shown in ochre. By combining this map with the surface constraints map, an overall favorability map can be generated.

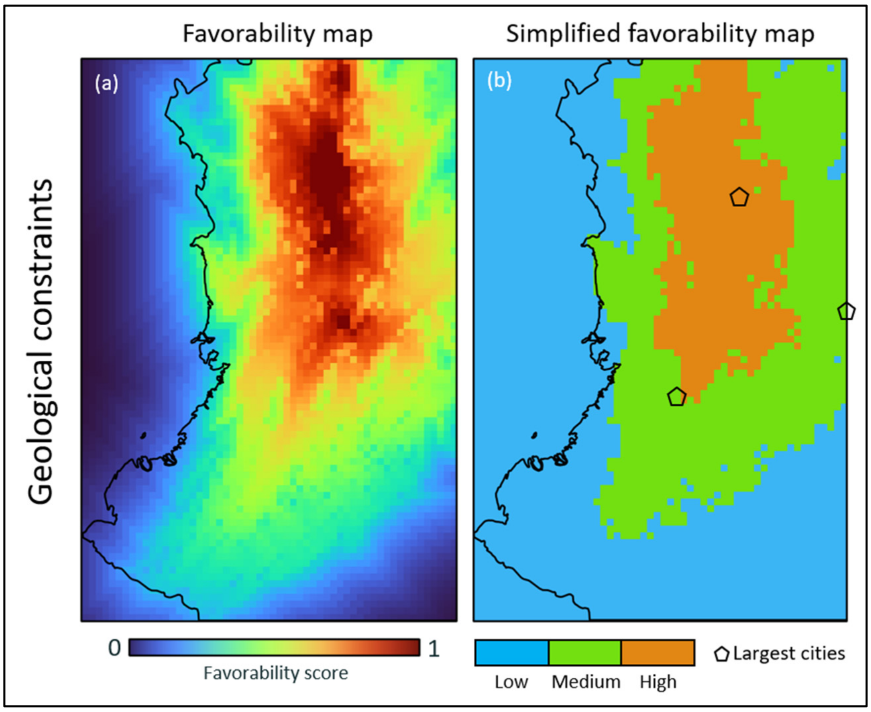

Figure 10. (**a**) Subsurface natural hydrogen presence favorability as computed based on maps in Figures 8 and 9. (**b**) Reclassified hydrogen presence favorability based on three discrete levels: weak (blue), medium (green), and high favorability (orange). Black pentagons represent the largest cities. The chosen thresholds for b are 0.0 to 0.4 for low presence favorability, 0.4 to 0.8 for medium, and above 0.8 for high favorability.

4.2.4. Ranking and Synthesis

Subsurface favorability maps remain invariant regardless of the end-market targeted by the operator (Table 2). Conversely, surface constraints vary by scenario, and the resulting composite maps are modeled from the perspective of a market new entrant (wherein active oil and gas concessions constitute exclusion zones). Absolute exclusion zones (delineated in gray) are an overlying spatial mask across the PFA. The PFA workflow involves a sequential spatial cross-comparison of the surface parameter maps—representing both energy poverty and industrial use—with the subsurface natural hydrogen favorability map. This overlay analysis generates a new synthesis map (Figure 11) within the same spatial domain, reclassified into four distinct favorability tiers:

1. Absence of both subsurface hydrogen and surface demand (blue + blue $\geq$ blue);
2. Co-occurrence of only one of the two factors (blue + green or blue + orange $\geq$ green);
3. Co-occurrence of both subsurface hydrogen and surface demand (green + green and green + orange $\geq$ orange);
4. Co-occurrence of high subsurface favorability and high surface demand (orange + orange $\geq$ red).

In the industrial market support scenario (Scenario B), maximum favorability is concentrated within a large continuous zone of approximately 3000 km^2 in the north–northeast sector (Antioquia Department). This area accounts for only about 1% of the study area, and this approach, although simple, is therefore highly selective. The Scenario B spatial distribution contrasts sharply with the energy poverty scenario, where peak favorability zones are highly fragmented across the territory, forming small clusters ranging from 100 to 600 km^2. These clusters are predominantly situated in the NW region, between Medellín and Planeta Rica, with some other zones south of Cali in the Valle del Cauca, and south of Bogotá. In both scenarios, the southern part of the study area remains highly unfavorable. Conversely, the valley between the Central and Western Cordilleras exhibits generally high favorability, though it is currently constrained by pre-existing mining concessions. To refine this predictive framework, future research should incorporate advanced geophysical data to better constrain potential source rocks and develop a more sophisticated migration model.

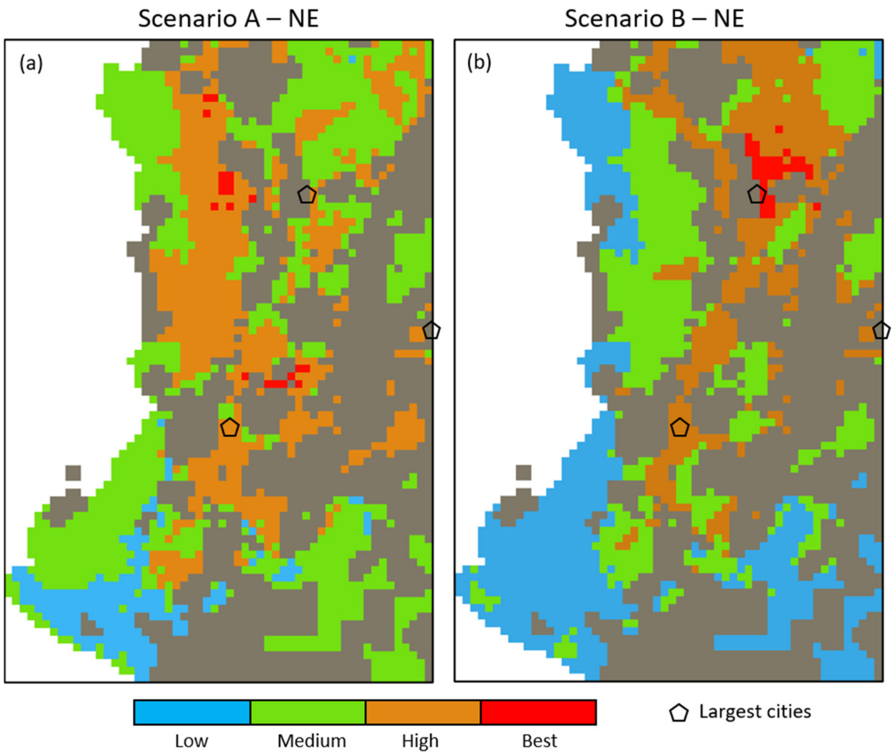

Figure 11. Favorability maps for the two studied scenarios. (**a**) Local use for reducing energy insecurity. (**b**) Sale of H_2 to the industrial markets. The gray areas are exclusion zones where H_2 exploration will not be possible, and the polygons represent the three major cities—Medellín, Bogotá, and Cali—from north to south.

Table 2. Areas that are more or less attractive for H_2 exploration, depending on the objectives of Scenarios A and B. Based on the maps in Figure 11.

Favorability	Scenario A		Scenario B	
	Nb of Cells	**% of the Area**	**Nb of Cells**	**% of the Area**
Best areas (red)	20	0.56	35	1
Good areas (orange)	715	20.1	491	13.8
Mid-range zones (green)	1058	29.7	708	19.9
Low favorability zones (blue)	189	5.3	748	21
Restricted zones (total exclusion)	1577	44.3	1577	44.3

5. Conclusions

While the Play Fairway Analysis (PFA) developed herein simplifies the underlying physical processes and possesses inherent limitations, it offers a robust decision-making framework capable of integrating a broad spectrum of heterogeneous criteria. Compared to maps such as those produced in Quebec [51] or by the USGS in the United States [11], taking surface constraints into account allows for a much more selective approach and, as a result, eliminates more than 80% of the study area based on the selection criteria used here. Other weightings may be chosen, but in terms of selectivity, it is worth noting that Scenarios A and B are very different, yet both agree that a large part of the study area would, as of now, be very risky for industrial development.

Once the overall picture has been established, this type of approach allows for more detailed analysis; energy insecurity in Colombia is closely linked to rainfall. An operator could adopt a hybrid off-take strategy, supplying power generation during drought periods and supplying fertilizer feedstocks during high-rainfall years. The intermontane corridor spanning Medellín, Cali, and its southern valley extension represents a strategic compromise for dual-market targeting. It has been assumed here that the companies knew in advance which market they were targeting, but it is also possible that the size of the deposit and the daily production rate may have dictated that choice retroactively. The broader Cali region—extending approximately 100 km along north–south axes—offers moderate multi-use suitability, despite lacking optimal conditions for either single application.

In conclusion, local factors are much more important at this stage of natural H_2 industry development than for many other raw materials. Land-use constraints are also much more significant in a country like Colombia than in others where infrastructure is more developed, and the terrain is less mountainous. Unlike world-class petroleum or mineral discoveries, where massive capital outlay justifies dedicated infrastructure buildout, the early-stage natural H_2 sector cannot yet rely on such capital intensity.

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Abbreviations

The following abbreviations are used in this manuscript:

HC	HydroCarbon
E&P	Exploration and Production

OPEX	OPerational EXpenses
CAPEX	CAPital EXpenses
PFA	Play Fairway Analysis
NE	New Entrant

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