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Is Green Hydrogen a Strategic Opportunity for Albania? A Techno-Economic, Environmental, and SWOT Analysis

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Abstract

Hydrogen is increasingly recognized as a clean energy vector and storage medium, yet its viability and strategic role in the Western Balkans remain underexplored. This study provides the first comprehensive techno-economic, environmental, and strategic evaluation of hydrogen production pathways in Albania. Results show clear trade-offs across options. The levelized cost of hydrogen (LCOH) is estimated at 8.76 €/kg H_2 for grid-connected, 7.75 €/kg H_2 for solar, and 7.66 €/kg H_2 for wind electrolysis—values above EU averages and reliant on lower electricity costs and efficiency gains. In contrast, fossil-based hydrogen via steam methane reforming (SMR) is cheaper at 3.45 €/kg H_2, rising to 4.74 €/kg H_2 with carbon capture and storage (CCS). Environmentally, Life Cycle Assessment (LCA) results show much lower Global Warming Potential (<1 kg CO_2-eq/kg H_2) for renewables compared with ~10.39 kg CO_2-eq/kg H_2 for SMR, reduced to 3.19 kg CO_2-eq/kg H_2 with CCS. However, grid electrolysis dominated by hydropower entails high water-scarcity impacts, highlighting resource trade-offs. Strategically, Albania's growing solar and wind projects (electricity prices of 24.89–44.88 €/MWh), coupled with existing gas infrastructure and EU integration, provide strong potential. While regulatory gaps and limited expertise remain challenges, competition from solar-plus-storage, regional rivals, and dependence on external financing pose additional risks. In the near term, a transitional phase using SMR + CCS could leverage Albania's gas assets to scale hydrogen production while renewables mature. Overall, Albania's hydrogen future hinges on targeted investments, supportive policies, and capacity building aligned with EU Green Deal objectives, with solar-powered electrolysis offering the potential to deliver environmentally sustainable green hydrogen at costs below 5.7 €/kg H_2.

Keywords: renewable hydrogen production; levelized cost of hydrogen (LCOH); life cycle assessment (LCA); hydrogen economy; SWOT analysis; barrier analysis; strategic energy planning; green energy transition; Albania

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1. Introduction

Energy sustainability is a major socio-environmental concern of the twenty-first century [1], with the global economy attempting to match growth with climate targets. Energy continues to drive economic growth and has a significant impact on international relations, influencing trade, security, and global power dynamics [2]. In this global context, the EU faces energy challenges that threaten its strategic autonomy, including import dependency, market volatility, and geopolitical risks—especially from reliance on Russian gas—highlighting the urgent need for greater connectivity, diversification, and investment in clean, secure energy. Achieving a sustainable future demands energy from non-fossil sources that is reliable, safe, adaptable, affordable, and abundantly available [3].

Rapid urbanization and economic growth in many emerging economies have driven a surge in energy demand [4]. In Western Balkan countries, energy systems face severe vulnerabilities affecting energy security, economic growth, and environmental sustainability. The region's power sector is the most polluting in Europe [5], challenged by rising electricity costs, aging fossil-based plants, and climate change impacts on hydropower. In Albania, where hydropower supplies 98% of electricity, these challenges are compounded by high energy imports and aging infrastructure [6]. The energy environment is further complicated by a high dependence on imported fuels for transportation, heating, and industrial purposes. Albania benefits from domestic oil production but still imports refined petroleum products and lacks natural gas infrastructure [7]. To achieve its national energy strategy targets [7]—namely, 20% natural gas penetration, 42% renewable energy generation, and transmission losses below 10% by 2030—the country must diversify and expand its portfolio of non-hydropower renewable sources. Because of their intermittent nature, renewable resources can negatively affect the stability, reliability, and quality of the grid [8]. To counter these effects, advanced storage solutions are crucial for strengthening system resilience and balance.

Hydrogen technologies, such as fuel cells and electrolyzers, are increasingly regarded as critical enablers of energy storage and decarbonization, hence promoting grid stability and the broader green transition [9]. They offer high energy density and conversion efficiency, environmental compatibility, and versatility [10]. Clean hydrogen in fuel cells supports transport, distributed heating, and storage systems, releasing water as the only byproduct [11]. The global fuel cell market is forecasted to expand markedly, rising from USD 9.85 billion in 2023 to 105.01 in 2032, driven by growing demand for clean energy and supportive policy frameworks [12]. In Europe, deployment reached 13,200 fuel cell units in 2022, totaling 228.1 MW of installed capacity—with the most substantial growth (186.9 MW) occurring between 2018 and 2022 [13]. These market trends signal a clear transition of fuel cell technologies from niche innovation to mainstream energy solutions.

The European Union expects hydrogen to be a key component of future energy systems [14]. Policy measures such as the REPowerEU Plan (2022), which aims to produce 10 Mt of domestic renewable hydrogen by 2030, and the Net-Zero Industry Act (2023), which aims to promote clean technology manufacturing, prioritize hydrogen in EU decarbonization strategies. Despite its potential to support energy-sector decarbonization, green hydrogen remains hindered by costly production [15]. At present, conventional production methods represent 95.6% of total capacity [13]. However, increasing access to renewables, competitive energy costs, legislative support, and solid offtake agreements are driving the expansion of electrolytic hydrogen plants, particularly in Nordic, Iberian, and Western European countries.

With rising academic and policy interest, studies are examining the cost-effectiveness of hydrogen production and its potential contribution to future energy systems. A 2021 UK Government BEIS report [16] estimated that off-grid electrolysis powered by offshore wind (with a capacity factor of 51%) would result in an LCOH of 5.13 EUR/kg H_2 by 2025, excluding compression and storage costs. Similarly, the International Council on Clean Transportation [17] projected a hydrogen cost of 5–6 EUR/kg H_2 for a 1 MW grid-connected PEM electrolyzer with a 95% capacity factor in the EU, with country-specific variations driven by electricity prices and capital costs. The European Hydrogen Observatory [13] estimates 2023 hydrogen production costs in Europe at 3.5–4.41 EUR/kg H_2 for steam methane reforming (without CAPEX), 4.41 EUR/kg H_2 with carbon capture, 4.06–17.36 EUR/kg H_2 via electrolysis depending on energy source and infrastructure. By 2030, the International Energy Agency [18] expects EU hydrogen costs could drop to 1.8–3.6 EUR/kg H_2, assuming low electricity prices (35.71 EUR/MWh) and high electrolyzer utilization rates. In Austria, Povacz and Bhandari [19] reported cost of hydrogen to range from 3.08 to 13.12 EUR/kg H_2, influenced by system design and site-specific factors. Recent studies show a wide range of costs, from as low as 3.01 EUR/kg using hybrid PV-wind off-grid systems in Austria [20] to as high as 57.61 EUR/kg for battery-buffered PV-electrolysis systems with limited scale and high CAPEX in Germany [21]. Intermediate costs include 3.35 EUR/kg in the Netherlands [22], 6.7 EUR/kg in Sweden [14], and 7–15.08 EUR/kg for off-grid renewable systems with integrated storage [23], reflecting the strong influence of system configuration, capital costs, and capacity factors.

Albania has a lot of potential for deploying hydrogen because of its abundant renewable energy sources, particularly hydropower, and its strategic location for regional energy integration. However, the nation faces obstacles such relatively high electricity costs in the Western Balkans, a lack of infrastructure associated with hydrogen, and the lack of demand-side incentives or specific laws. Since electricity prices largely determine the economic feasibility and the levelized cost of hydrogen (LCOH), electrolysis-based production is particularly sensitive to these cost dynamics [13]. Beyond cost-related constraints, the policy dimension plays a critical role. As Wu et al. [24] demonstrate in the context of carbon trading, incentive mechanisms that are not carefully structured can unintentionally destabilize markets, despite promoting low-carbon transitions. This insight is relevant for Albania, where emerging hydrogen frameworks will need to strike a balance between investor confidence and effective decarbonization incentives. Moreover, trade-offs among environmental impacts must be considered to ensure genuine sustainability. Even electrolysis-based hydrogen, often regarded as clean, has been shown to generate substantial environmental burdens across impact categories [25–27]. This combination of opportunities and constraints underscores the need for a comprehensive assessment that integrates both techno-economic feasibility and systemic factors influencing hydrogen deployment. The Strengths, Weaknesses, Opportunities, and Threats (SWOT) framework—examining strengths, weaknesses, opportunities, and threats—serves as a strategic instrument to evaluate both internal capacities and external conditions influencing the development of emerging energy sectors. SWOT analysis has been widely used to evaluate hydrogen readiness and guide national strategies in diverse contexts. Similar analyses have been carried out in China [28], Iran [29], North Africa [30], Brazil [31], Türkiye [32], Poland [33] and Gulf countries [34]. Simões and Santos [35] performed a SWOT analysis of green hydrogen market using an extensive literature review. These studies provide structured insights into internal capacities and external conditions affecting hydrogen market development, including policy frameworks, technological capabilities, and investment landscapes. Applying this method to Albania enables a strategic understanding of its potential to transition toward a hydrogen-based economy, while identifying enablers, barriers, and leverage points for action.

This study presents a first-of-its-kind assessment of hydrogen production in Albania, integrating levelized cost of hydrogen (LCOH) modeling, a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis, and a streamlined life cycle assessment (LCA). Applying this method to Albania enables a strategic understanding of its potential to transition toward a hydrogen-based economy, while identifying enablers, barriers, and leverage points for action. Beyond the Albanian context, the country's structural features—renewable resource abundance, infrastructure gaps, policy uncertainty, and integration with EU markets—are broadly representative of challenges faced by many developing economies. Framing

Albania as a test case, therefore, enhances the global relevance of this study, offering transferable insights for similar contexts.

2. Materials and Methods

2.1. Research Design

This study adopts a multi-dimensional methodology to evaluate the feasibility of hydrogen production in Albania. A techno-economic analysis quantifies the levelized cost of hydrogen (LCOH) for three renewable electrolysis pathways—grid-connected, solar-powered, and wind-powered. For comparison, two fossil-based alternatives are included: steam methane reforming (SMR) with and without carbon capture and storage (CCS). To complement the economic perspective, a streamlined life cycle assessment (LCA) is conducted to estimate the environmental impacts of hydrogen production across pathways. The analysis emphasizes key indicators such as greenhouse gas emissions, water-scarcity footprint, and aggregated environmental performance metrics.

To capture broader systemic factors, a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis is undertaken, examining enablers and barriers to hydrogen market development in Albania. The framework integrates technical, economic, policy, and market dimensions, drawing on both primary inputs (stakeholder consultations, project data) and secondary sources (peer-reviewed literature, regulatory documents, energy pricing reports).

Finally, a sensitivity analysis is conducted to examine how major cost drivers (e.g., capital investment, electricity prices, and capacity factors) influence the LCOH results. Together, these approaches provide a comprehensive assessment: the LCOH analysis establishes the economic feasibility baseline, the LCA highlights environmental trade-offs, and the SWOT situates these findings within Albania's strategic, infrastructural, and policy context.

2.2. Economic Feasibility Analysis

The economic viability was conducted using the levelized cost of hydrogen (LCOH), a financial metric that captures all costs incurred over the lifetime of a hydrogen production system [36]. These costs include capital expenditures (CAPEX), fixed and variable operational expenditures (OPEX), and electricity and fuel (if any) expenses, relative to the total hydrogen produced over the system's operational period (Equation (1)). A lower LCOH reflects a more cost-effective hydrogen production pathway, indicating higher economic competitiveness [36,37].

$$\mathrm{LCOH} = \frac{\mathrm{LHV}}{\eta_{\mathrm{sys,LHV}}} + \left(\left(\frac{\left(\frac{i}{100} * \left(1 + \frac{i}{100}\right)^{n} \right)}{\left(1 + \frac{i}{100}\right)^{n} - 1} + \frac{\mathrm{OPEX}}{100} \right) \frac{\mathrm{CAPEX}}{\tau} + E \right) \tag{1}$$

where LCOH: levelized cost of hydrogen [€/kg H_2]; LHV: Lower Heating Value [kWh/kg H_2]; i: Discount Rate [%]; n: Lifetime [a]; E: Electricity Costs [€/kWh]; $\eta_{\mathrm{sys,LHV}}$: system efficiency related to the LHV; τ: Full Load Hours [h]; OPEX: Operational Expenditures [CAPEX/a]; CAPEX: Capital Expenditures [€/kW].

For the LCOH calculation, the Excel tool (v1.0, 2023 edition) from Umlaut & Agora Industry [38] is used. This model enables the estimation of hydrogen production costs by incorporating adjustable parameters such as electricity prices, discount rates, system lifetime, energy consumption, and operating hours. It was designed to be user-friendly, grounded in EU benchmark studies, and validated against reference cases published by Agora Industry and Hydrogen Europe [38].

For this study, the tool was customized using Albania-specific parameters. The economic and technical parameters considered in the LCOH calculation are presented in Table 1. Electricity prices, sourced from the Albanian Energy Regulatory Authority [39], include all applicable charges and retail electricity tariffs for customers. Specific energy consumption (kWh/kg H_2) accounts for both electrolysis and auxiliary power requirements. The conversion from electrolysis capacity (MW_{el}) to annual hydrogen output (tonnes/year) was calculated assuming an overall energy demand of 58 kWh per kilogram of hydrogen produced. This value accounts for 53 kWh/kg H_2 associated with stack efficiency [40] and an additional 5 kWh/kg H_2 for storage requirements. Hydrogen storage requires 2.9 kWh/kg H_2 at 350 bar and 3.7 kWh/kg H_2 at 700 bars for compression [41]. For low-temperature electrolyzers, energy consumption is typically 55–60 kWh per kg of hydrogen produced [42].

Table 1. Key economic and technical parameters for LCOH calculation.

Parameter	Amount	Unit	Source
Energy consumption *	58	kWh/kg H_2	[40,41]
Price grid-electricity	126.5	€/MWh	
Price PV-based electricity	76	€/MWh	[39]
Price wind-based electricity	100	€/MWh	
Price natural gas	65	€/MWh	[39]
Capital investment, SMR	900	€/kW	[36]
Capital investment, alkaline electrolyzer	1666	€/kW	[12]
Capital investment, proton exchange membrane (PEM) electrolyzer	1970	€/kW	[12]
OPEX	3.5	% of CAPEX	[12]
Discount rate	5	%	Own assumption (based on project appraisal practice)
Economic lifetime	20	Years	[12]

* H_2 gas compressed to high pressure (350 and 700 bar).

For grid-connected electrolysis, we assume 8320 full-load hours, reflecting continuous operation. For renewable-powered pathways (solar and wind), full-load hours are adjusted to reflect real-world variability in resource availability. In Albania, PV systems typically operate around 2000–2500 h/year, while wind systems average 3000–4000 h/year depending on site conditions. The capital investment was assumed at 1666 €/kW for alkaline electrolyzers and 1970 €/kW for proton exchange membrane (PEM) electrolyzers. Operational expenditures (OPEX) typically range from 1.5% to 5% of CAPEX [12], with this study adopting a value of 3.5%.

For SMR-based hydrogen, the calculation assumes CAPEX of 900 €/kW, OPEX of 3.5% per year, discount rate of 5% (assumed based on appraisal practice), plant lifetime of 20 years, and thermal efficiency of 70% (LHV). The natural gas price of 65 €/MWh was used, with hydrogen's LHV taken as 33.33 kWh/kg. For SMR + CCS, a 94% CO_2 capture rate and 100 €/t CO_2 transport and storage were assumed [43].

Limitations of the tool include its static, average-based design and lack of country-specific modules or automatic regional scaling. It does not account for fluctuations in carbon pricing, transmission costs, or dynamic learning rates. Furthermore, it lacks built-in uncertainty propagation or Monte Carlo simulation. To address these limitations, a sensitivity analysis was carried out to evaluate the effect of:

1. $\pm$25% variations in electricity prices on LCOH;
2. Improvements in electrolyzer efficiency on hydrogen costs; and
3. Differences in hydrogen production scale (small vs. large installations).

This analysis helps identify key cost drivers and investment risks for hydrogen deployment in Albania.

2.3. SWOT Analysis

The SWOT analysis assessed internal (strengths and weaknesses) and external (opportunities and threats) factors shaping Albania's hydrogen economy, offering stakeholders insights to guide strategic planning for hydrogen adoption and expansion. The SWOT matrix was informed both by primary insights gathered during stakeholder consultations within the EkoALport project and by comparative findings from international hydrogen economy assessments [28–35]. Stakeholder engagement involved a series of structured meetings and discussions with key national institutions, including the Ministry of Energy and Infrastructure, Durrës Port Authority, Albanian Investment Development Agency (AIDA), Albanian Aviation Council, KfW Development Bank, and the National Employment and Skills Agency (NAES). These actors were selected due to their strategic relevance to energy infrastructure and the high energy demand of ports and airports—identified as priority nodes for future hydrogen deployment. Given the strategic role of ports and airports as high-energy-demand sectors and potential hydrogen hubs, their inclusion was essential in assessing both feasibility and implementation challenges for hydrogen deployment in Albania. While this approach provided valuable contextual insights, its main limitation is that it remains qualitative, with no scoring, ranking, or weighting of factors applied. However, this process was deemed appropriate for the exploratory scope of the study, offering valuable contextual insights into the readiness, challenges, and opportunities of Albania's hydrogen economy.

2.4. Environmental Assessment: Streamlined Life Cycle Assessment (LCA)

To complement the techno-economic evaluation, a streamlined life cycle assessment (LCA) was applied to evaluate the environmental performance of hydrogen production routes in the Albanian context. Following international LCA standards, a cradle-to-gate system boundary was adopted for this study (Figure 1). The analysis included input resources (natural gas, electricity, steam, chemicals) through operation and decommissioning, covering both resource use and emissions. The functional unit is defined as 1 kg of gaseous hydrogen produced at the plant gate, ready for end-use application. For simplification, it is assumed that all energy use and emissions are attributed entirely to the hydrogen product, with no allocation or multi-functionality modeled.

Data on manufacturing process inventory were sourced from publications and datasets of the GREET model [44]. Key operational inputs included electricity (≈58 kWh/kg H_2) and water (≈9.1 L/kg H_2) for electrolysis [25], while natural gas (≈4.8 Nm^3/kg H_2) and process heat were the primary inputs for SMR, with slightly higher requirements under SMR + CCS (≈5 Nm^3/kg H_2) due to the energy penalty of CO_2 capture.

Key environmental impact categories taken into account were Global Warming Potential (GWP), cumulative energy demand (CED), water-scarcity footprint (WSF), and ReCiPe single score. The life cycle impact assessment (LCIA) was conducted using the scope 3 idemat dataset version Idemat 2025RevA6.xlsx [45]. The water-scarcity impact assessment used characterization factors from the AWARE (Available WAter REmaining) methodology, developed by the WULCA working group [46].

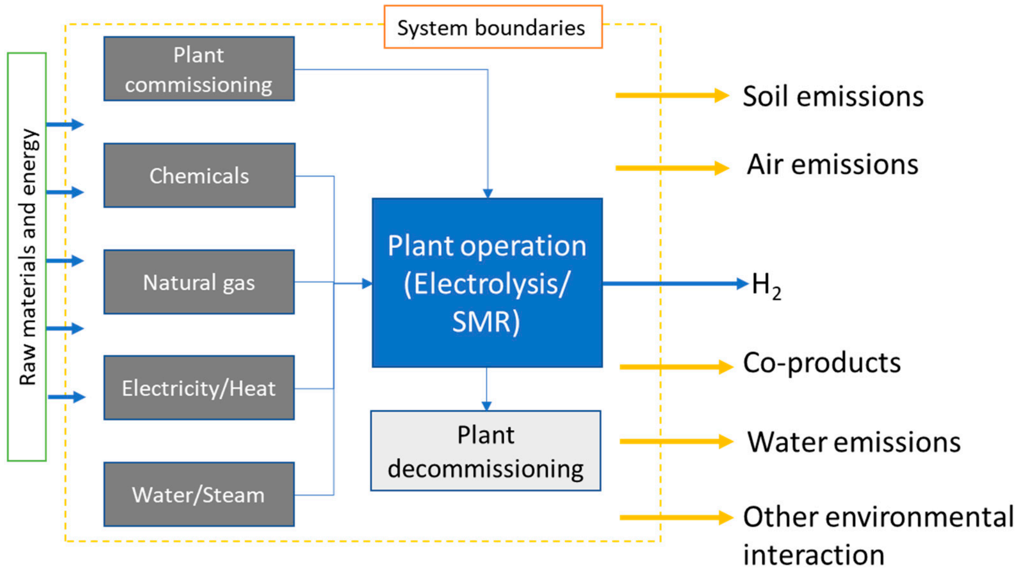

Figure 1. System boundaries for the LCA of hydrogen production pathways, including inputs, plant processes, and outputs (modified from Mehmeti et al. [25]).

3. Results

3.1. LCOH of Hydrogen Production in Albania

Figure 2 presents the calculated levelized cost of hydrogen (LCOH) in Albania across different production pathways. Grid-connected electrolysis is identified as the most expensive option, with an LCOH of 8.76 €/kg H_2 (7.62–9.9 €/kg H_2), primarily due to high electricity costs (126.5 €/MWh), which account for nearly 84% of operational expenses. When operating at higher full-load hours, the main cost drivers shift to electricity costs and system efficiency, rather than investment costs. Thus, the cost of hydrogen from grid-connected electrolysis can be significantly lowered by decreasing electricity prices, improving system efficiency, and maximizing annual full-load hours [13,41].

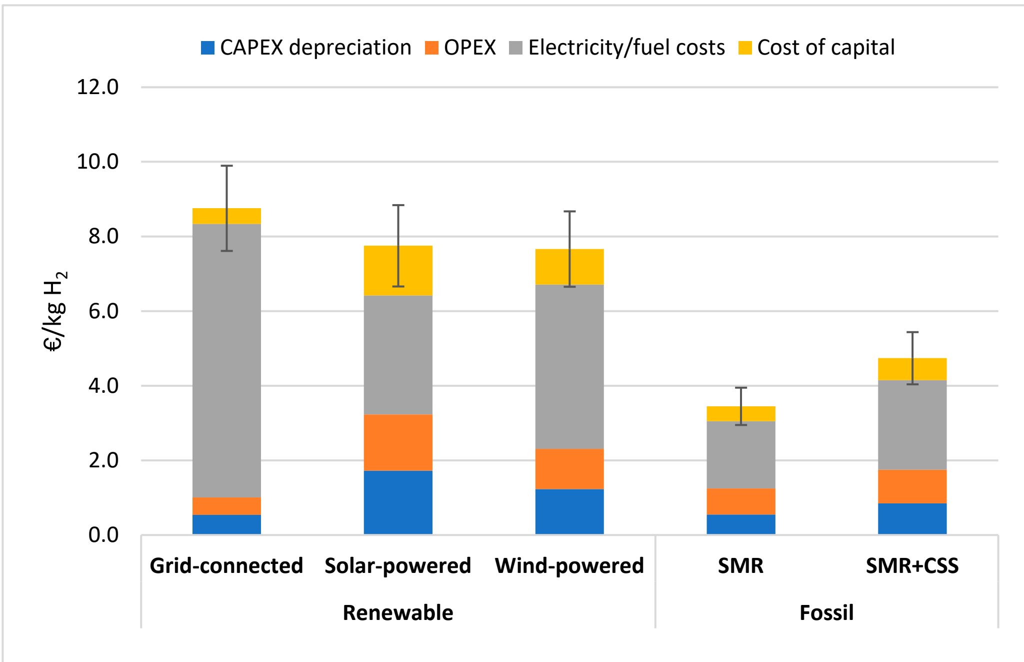

Figure 2. Levelized cost of hydrogen (LCOH) production in Albania. Standard deviations are indicated with a black line.

Wind-powered electrolysis, with an LCOH of 7.66 €/kg H_2 (6.65–8.67 €/kg H_2), remains the lowest-cost option under current conditions. It balances moderate CAPEX (1.2 €/kg H_2), OPEX (1.1 €/kg H_2), and electricity costs (78.5 €/MWh), making it a highly competitive alternative for green hydrogen production. However, site-specific wind resource availability and infrastructure investments remain key factors in determining its long-term feasibility.

Solar-powered electrolysis offers a lower LCOH 7.75 €/kg H_2 (6.66–8.84 €/kg H_2) due to reduced electricity costs (55 €/MWh), despite higher CAPEX (1.7 €/kg H_2) and OPEX. For annual PV full-load hours below the ~3000 h threshold, the investment costs of the electrolysis system represent the majority of the total hydrogen production costs.

A notable development in Albania's solar energy market is the Karavasta Solar Park (https://karavastasolar.com), where the winning bid in an international auction, announced by the Ministry of Infrastructure and Energy, set a price of 24.89 €/MWh—the lowest in the region. To further illustrate site-specific advantages, we recalculated LCOH for solar-powered electrolysis using the Karavasta auction price (24.89 €/MWh). This results in an LCOH of 5.68 €/kg H_2, indicating that solar hydrogen can become highly competitive under favorable procurement conditions and capacity factors above 2500 h/year. The cost is markedly lower than Albania's wholesale electricity prices (50–55 €/MWh), underscoring the strong potential of solar-powered hydrogen. The affordability of renewable hydrogen production is expected to be further enhanced by future advancements in electrolyzer technology (e.g., lower CAPEX and improved efficiency) and the continued decrease in solar PV costs.

Electricity markets in the Western Balkans are characterized by significantly higher volatility due to hydropower dependence, import exposure, and limited market integration. Therefore, actual fluctuations in electricity prices and capacity factors may exceed the assumed range, which could shift the competitiveness of different hydrogen pathways. Addressing this uncertainty will require scenario-based modeling that accounts for larger parameter deviations and stress-test conditions.

For comparison, steam methane reforming (SMR)—the most widespread global hydrogen production method—achieves the lowest cost at 3.45 €/kg H_2 under Albanian market assumptions, driven by relatively low CAPEX and OPEX requirements. When paired with carbon capture and storage (SMR + CCS, 94% capture rate), costs increase to 4.74 €/kg H_2 due to additional capture equipment, higher operating expenses, and increased energy demand. While SMR-based options remain cost-competitive, their long-term adoption in Albania will depend on carbon pricing policies, infrastructure readiness, and access to suitable CO_2 storage sites.

3.1.1. Comparison of LCOH with Other European Countries

Figure 3 displays the calculated costs of producing hydrogen with grid electricity across Europe in 2023. The LCOH for grid-based hydrogen was estimated to be in the range of 4.06–17.4 EUR/kg, with the average for all countries being 7.94 EUR/kg and a median of 7.53 EUR/kg [47]. Albania's LCOH (8.76 €/kg H_2) is higher than the European average, placing it among the more expensive hydrogen markets. It also exceeds the LCOH of most neighboring countries, including Bulgaria (7.4 €/kg H_2), Greece (7.4 €/kg H_2), Romania (8.3 €/kg H_2), and Croatia (8.1 €/kg H_2). However, Albania's LCOH remains lower than that of countries such as Germany (9.2 €/kg H_2), Hungary (10 €/kg H_2), Italy (10.1 €/kg H_2), and Poland (12.4 €/kg H_2), where hydrogen production costs are even higher. Countries with cheaper LCOH typically benefit from abundant low-cost renewable electricity, such as hydropower (Norway), wind (Denmark), or solar (Portugal).

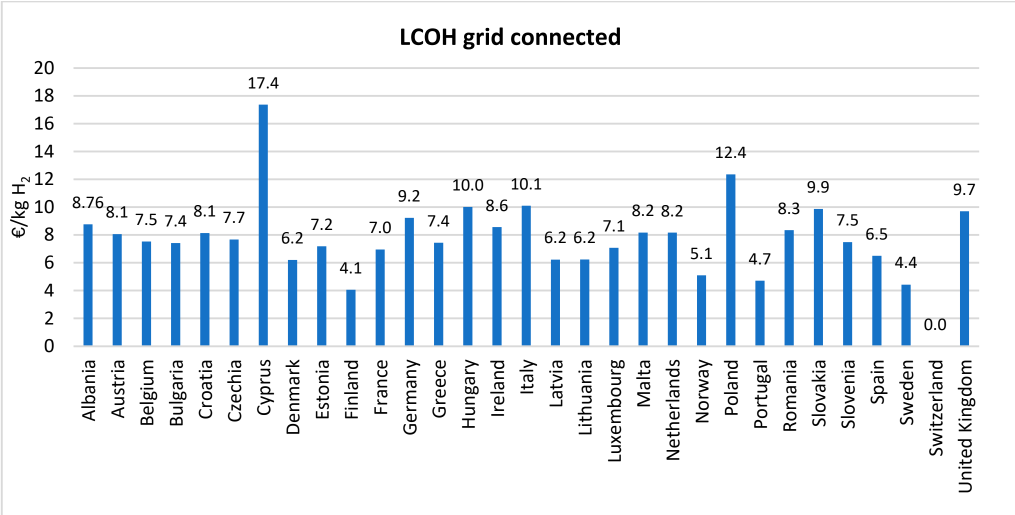

Figure 3. Comparative LCOH from grid-connected electrolysis in Albania versus selected European countries in 2023 (data from [47]).

Figure 4 shows LCOH from renewable sources across European countries. Hydrogen production via electrolysis directly connected to renewable energy sources in Europe varies from 4.13 to 9.30 €/kg H_2, with an average of 6.61 €/kg H_2 and a median of 6.20 €/kg H_2 [47]. In Albania, the average levelized cost of hydrogen (LCOH) from renewable sources is 7.71 €/kg H_2, placing it above both the European median and average, making it one of the more expensive markets for renewable hydrogen production. However, it remains within the overall European range, indicating room for cost reduction through targeted strategies. Albania's LCOH surpasses that of Greece (5.1 €/kg H_2), Croatia (7.4 €/kg H_2), and Poland (7.2 €/kg H_2), but remains lower than Romania (8.2 €/kg H_2), Slovakia (8.3 €/kg H_2), and Slovenia (8.6 €/kg H_2). Countries with the lowest LCOH, such as Norway (4.3 €/kg H_2), Ireland (4.1 €/kg H_2), Sweden (5.0 €/kg H_2), Denmark (4.7 €/kg H_2), and Spain (5.6 €/kg H_2), benefit from low-cost renewable electricity sources, particularly hydropower, wind, and solar energy. In contrast, Germany (8.9 €/kg H_2), Belgium (8.4 €/kg H_2), and Luxembourg (9.3 €/kg H_2) experience higher LCOH, likely due to higher renewable infrastructure costs and less favorable energy market conditions.

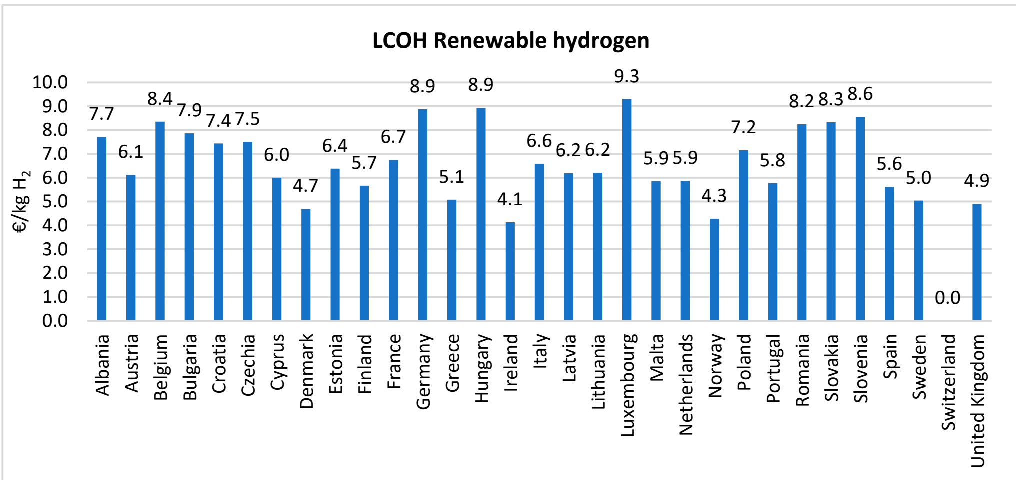

Figure 4. Comparative LCOH from renewable-powered electrolysis in Albania versus selected European countries in 2023 (data from [47]).

Albania's relatively high LCOH highlights the urgent need to reduce electricity costs and enhance system efficiency to improve competitiveness. Achieving this requires scaling up renewable capacity (particularly solar and wind), improving grid integration, and deploying energy storage solutions. According to recent literature [13,16,17], hydrogen production costs vary significantly across Europe. LCOH estimates range from €3–6/kg under optimal conditions to over €17/kg, depending on factors like electricity prices, system configuration, and scale. Falling within the upper range of these benchmarks, Albania's LCOH emphasizes the need for strategies to reduce costs to maintain competitiveness in the European hydrogen market as it develops. Electrolysis-based hydrogen production that is directly connected to renewable energy sources (like solar or wind) offers a cost advantage by removing expenses related to electricity, such as grid fees and network charges. This makes it a potentially more affordable alternative to grid-powered electrolysis. However, its economic and operational efficiency is limited by the intermittency of solar and wind resources, which impacts the utilization rate of electrolysis systems. To address these issues, Albania could adopt energy storage solutions, hybrid renewable systems, and advanced load management strategies to enhance system reliability and cost-effectiveness. By optimizing renewable hydrogen production and lowering costs, Albania can strengthen its position in the European hydrogen market, making green hydrogen a viable and competitive energy source for the country's transition to a sustainable economy.

Figure 5 shows LCOH from steam methane reforming across European countries [47]. At the EU level, the average levelized cost of SMR hydrogen in 2023 was approximately 3.76 €/kg H_2, with the lowest value observed in Spain (≈2.1 €/kg H_2) and the highest in Luxembourg (≈5.0 €/kg H_2). However, because many SMR facilities are already operational and, in some cases, fully amortized, marginal costs—which exclude CAPEX recovery and other fixed costs—can be a more relevant benchmark for short-term competitiveness. Under these conditions, the average marginal production cost in Europe was around 3.50 €/kg H_2. When carbon capture and storage (CCS) is integrated, the average European SMR hydrogen cost rises to 4.41 €/kg H_2. These figures highlight that SMR continues to be one of the most economically competitive hydrogen production pathways globally and in Europe. The same cost advantage holds true in the Albanian context, with natural gas price differentials influencing its competitiveness across different countries.

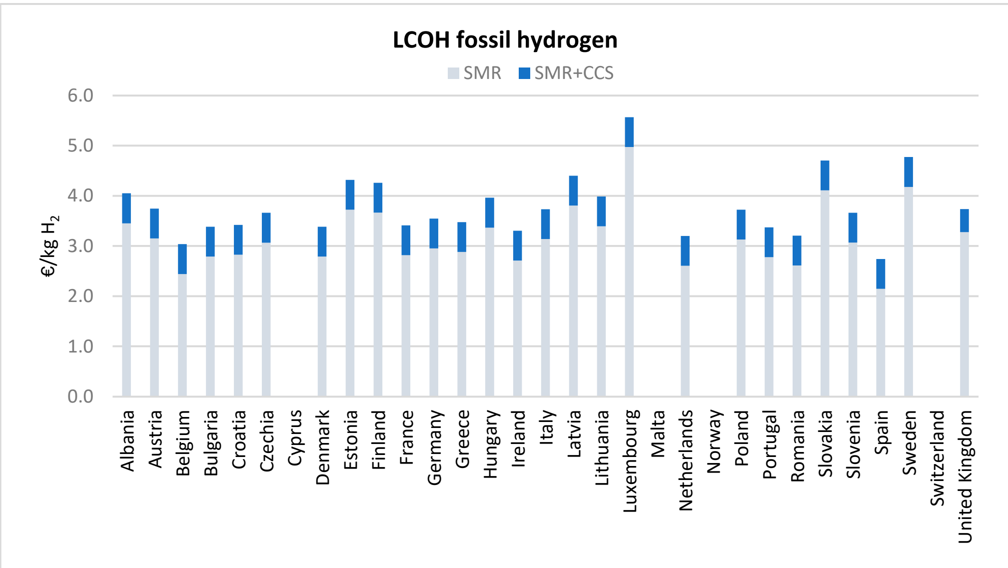

Figure 5. Comparative LCOH from steam methane reforming with and without carbon capture in Albania versus selected European countries in 2023 (data from [47]).

3.1.2. Environmental Performance Results

The results of environmental impact assessments of hydrogen production from various pathways per 1 kg of hydrogen are shown in Figure 6, specifically for Global Warming Potential (GWP), cumulative energy demand (CED), and water-scarcity footprint. The GWP analysis shows that grid-connected electrolysis in Albania achieves the lowest carbon footprint, at 0.42 kg CO_2-eq/kg H_2, due to the country's electricity mix being dominated by hydropower. This value is well below the median reported in a meta-analysis of 100 LCA studies by Puig-Samper et al. [48], which found a median of 19.75 kg CO_2-eq/kg H_2 and a range from 0.75 to 48.69 kg CO_2-eq/kg H_2 for grid-powered electrolysis, depending largely on grid composition. Busch et al. [49] similarly warn that electrolysis powered by carbon-intensive grids can exceed the GWP of conventional hydrogen, reinforcing the need to evaluate pathways in context. Shaya and Glöser-Chahoud [50] further show wide variability across electrolysis technologies, from ~1 to >30 kg CO_2-eq/kg H_2 for alkaline electrolysis and ~0.5 to <30 kg CO_2-eq/kg H_2 for PEM systems, highlighting sensitivity to both technology choice and electricity source. Among renewable-powered electrolysis routes, wind-powered hydrogen in Albania records a GWP of 0.48 kg CO_2-eq/kg H_2, slightly higher than grid electrolysis, while solar-powered hydrogen shows 0.71 kg CO_2-eq/kg H_2 due mainly to upstream emissions from photovoltaic panel manufacturing. These findings align with Ajeeb et al. [51], who report wind energy generally yields a lower GWP than solar in hydrogen production.

This study estimated the GWP of SMR to be 10.39 kg CO_2-eq/kg H_2, which is consistent with existing literature. Comparative LCA results from Mehmeti et al. [25] reinforce these trends, showing SMR without CCS at 12.13 kg CO_2-eq/kg H_2, PEM electrolysis powered by renewables at 2.21 kg CO_2-eq/kg H_2, SOEC electrolysis with renewables at 5.10 kg CO_2-eq/kg H_2, and coal gasification at 24.2 kg CO_2-eq/kg H_2. Across multiple studies, unabated SMR typically yields life-cycle GHG emissions in the range of 9–13 kg CO_2-eq/kg H_2 [25,52–54], while SMR with CCS can reduce emissions by 50–94% depending on capture efficiency and methane leakage rates [54].

The cumulative energy demand (CED) results, however, reveal another dimension. Grid-connected electrolysis shows the highest value at 220 MJ/kg H_2, driven by the energy intensity of hydropower infrastructure. Wind-powered hydrogen is similar at 214.9 MJ/kg H_2, while solar-powered electrolysis records the lowest renewable CED at 96 MJ/kg H_2, reflecting lower lifetime energy inputs in PV-based systems. For fossil-based pathways, SMR requires 180 MJ/kg H_2, while SMR with CCS slightly increases this to 191.9 MJ/kg H_2 due to capture and storage processes. This highlights the trade-off: renewables can drastically lower GHG emissions but may involve higher embodied energy in infrastructure compared to fossil-based options.

When water-scarcity impacts are considered through the AWARE indicator, a markedly different ranking emerges among the hydrogen production pathways. Grid-connected electrolysis in Albania shows the highest AWARE value at 49.38 m^3 world-eq/kg H_2, almost entirely driven by hydropower reservoir evaporation embedded in the electricity mix. Solar-powered electrolysis records an AWARE score of 2.02 m^3 world-eq/kg H_2, while wind-powered electrolysis is slightly lower at 1.94 m^3 world-eq/kg H_2; in both cases, the impacts are dominated by the manufacturing of photovoltaic modules or wind turbines and, for solar, water used in panel cleaning. Steam methane reforming without CCS has the lowest AWARE footprint at 0.37 m^3 world-eq/kg H_2, reflecting the relatively low water consumption in natural gas extraction and processing, along with direct process water requirements for steam production. However, this low water-scarcity burden comes at the expense of significantly higher GHG emissions, as noted in the GWP analysis. These results illustrate a key trade-off: while renewable-powered electrolysis pathways—particularly those using wind or solar—combine low GWP with low-to-moderate water-scarcity impacts, grid-powered electrolysis in hydropower-dependent systems can achieve exceptionally low GWP but at the cost of very high-water consumption in regions where water resources may be scarce. Conversely, fossil-based hydrogen from SMR offers minimal water-scarcity impacts but high GHG emissions, underscoring the need for integrated climate–water assessments when evaluating hydrogen production strategies.

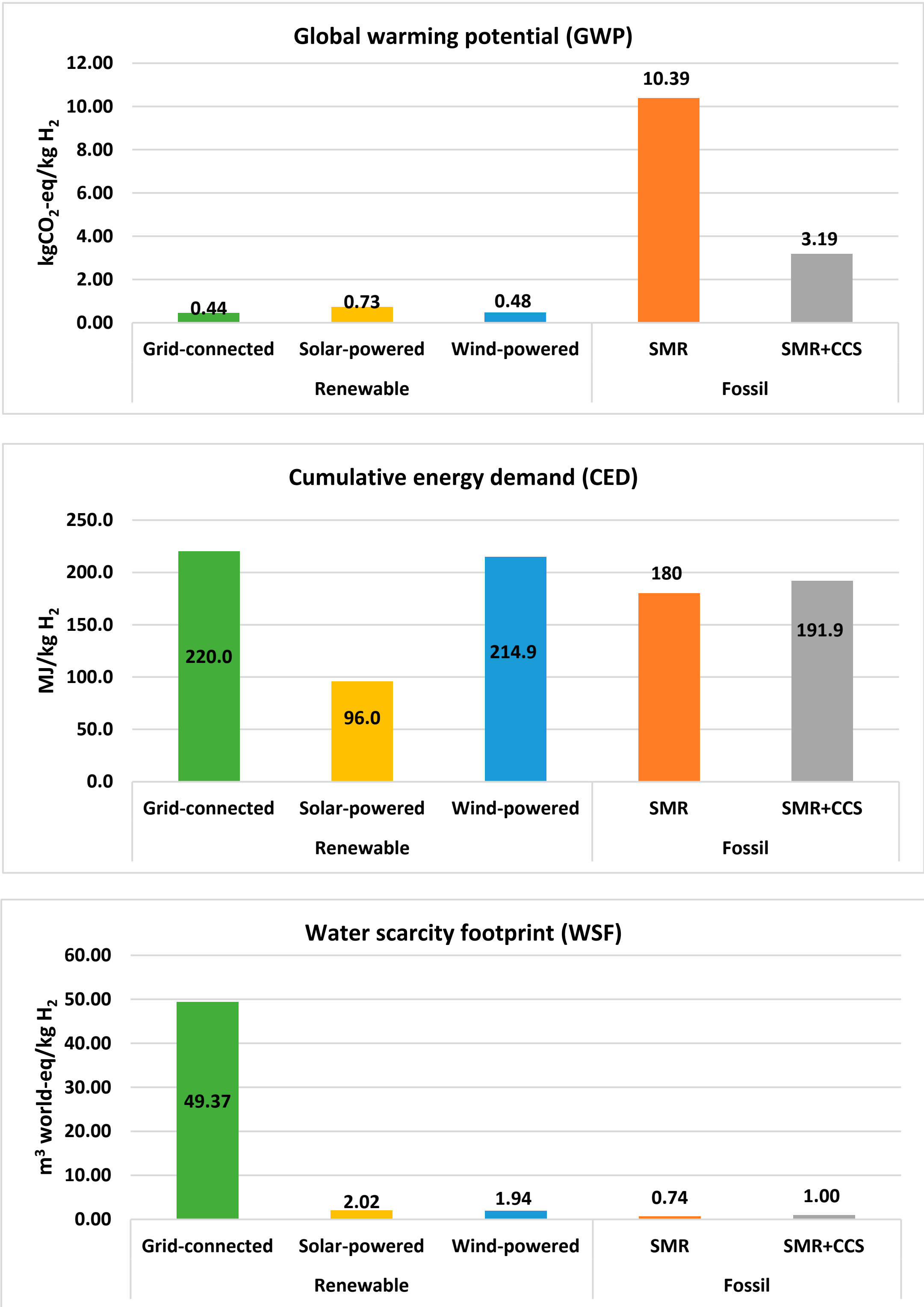

Figure 6. Global Warming Potential (GWP), cumulative energy demand (CED) and water-scarcity footprint (WSF) of hydrogen production in Albania.

The overall environmental burden (Figure 7) was evaluated using the ReCiPe2016 method, expressed in points per kilogram of hydrogen produced. The findings reveal a clear distinction between fossil-based and renewable-powered pathways. SMR without CCS records the greatest impact at 0.102 points/kg H_2, primarily from the upstream impacts of natural gas extraction and processing. Incorporating CCS reduces the score to 0.033 points/kg H_2, reflecting the additional energy and infrastructure requirements but a reduction in climate-related damages. Renewable-powered electrolysis pathways show much lower total ReCiPe scores, with values of 0.011, 0.012, and 0.012 points/kg H_2 for grid-connected, solar-powered, and wind-powered hydrogen, respectively. These low values are driven by Albania's low-carbon electricity mix and the relatively small upstream impacts from renewable energy technologies. Overall, the ReCiPe results reinforce the conclusions from the GWP and AWARE analyses: while SMR (even with CCS) carries a higher overall environmental burden, renewable-powered electrolysis pathways offer the most favorable balance between climate impact, water scarcity, and aggregated life-cycle impacts.

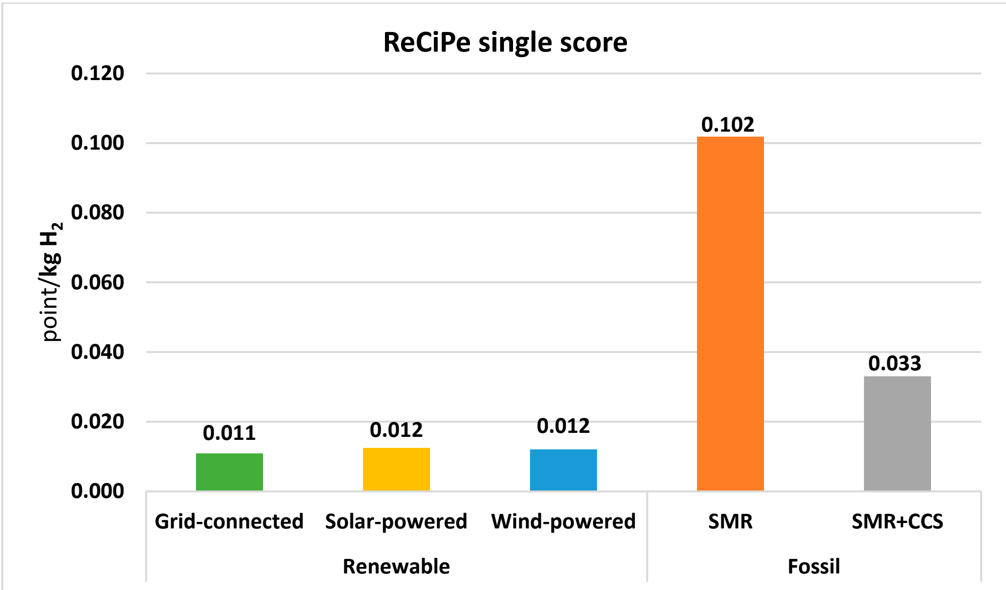

Figure 7. Overall environmental burden of hydrogen production in Albania via three electrolysis pathways, steam methane reforming (SMR), and SMR with carbon capture and storage (CCS), expressed using the ReCiPe2016 endpoint indicator in points per kilogram of hydrogen produced.

3.2. SWOT Analysis of Hydrogen Economy in Albania

Table 2 displays the detailed SWOT analysis of hydrogen economy in Albania.

3.2.1. Strengths

Albania's energy system possesses several unique strengths, positioning the country as a strong candidate for hydrogen development. The country's dominance in renewable energy production is a key advantage, with 98.98% of electricity generated from hydropower in 2023 (8,705,910 MWh out of 8,795,634 MWh). Additionally, Albania has seen steady growth in solar energy, increasing from 0 MWh in 2018 to 89,724 MWh in 2023, reflecting efforts to diversify its renewable energy mix. However, the current share of photovoltaics remains small, emphasizing the need for further investments in solar expansion to ensure a more balanced renewable energy portfolio for stable green hydrogen production. Albania's growing government interest in energy storage and diversification is evident through its large-scale renewable projects, such as the 140 MW Karavasta Solar Power Plant, commissioned in late 2023, and the successful auction of 222.6 MW wind farms. These projects are crucial for stabilizing renewable energy supply, as energy storage and grid flexibility are vital in boosting hydrogen production potential. By 2030, Qamili and Kapia [55] have calculated that Albania will have a technical potential of 7483 MW and an economic potential of 616 MW for wind energy, in addition to a technical potential of 2378 MW and an economic potential of 1074 MW for solar photovoltaic (PV) energy. Green hydrogen brings system-wide benefits, such as improving energy security, enabling greater integration of variable renewable energy (VRE), reducing air pollution, and creating new economic and employment opportunities [56].

Table 2. Strengths, weaknesses, opportunities, and threats for Albania's hydrogen economy.

Strengths	Weaknesses
• Predominance of renewable energy in the national electricity mix. • Availability of existing natural gas infrastructure. • Growing government focus on energy storage systems and diversification of the energy mix. • Increasing policy support and recognition for hydrogen technologies. • Strong alignment with EU Green Deal objectives. • Strategic geographical proximity to EU markets. • High potential for off-grid renewable hydrogen production.	• High production costs for green hydrogen. • Significant upfront capital investment requirements. • Absence of dedicated hydrogen distribution and storage infrastructure. • Limited political focus and delayed policy integration. • Lack of targeted financial incentives to support adoption. • Regulatory gaps and absence of comprehensive hydrogen legislation. • Limited domestic technical knowledge and expertise in hydrogen technologies.
Opportunities	**Threats**
• Diversification of the national energy mix using power-to-gas and gas-to-power. • Access to EU funding, as well as kfW, EBRD, and World Bank grants for hydrogen initiatives. • Potential to generate high-skilled jobs and attract foreign direct investment (FDI). • Declining costs of electrolyzers, fuel cells, and storage technologies, enhancing project feasibility. • Possibility to repurpose existing natural gas pipeline infrastructure. • Potential to develop a competitive green hydrogen export market.	• Competition from alternative renewable solutions, particularly solar combined with battery storage. • Public concerns and negative perceptions regarding hydrogen safety. • Persistently high production costs and challenges to economic viability. • Growing regional competition from neighboring countries advancing their hydrogen sectors. • Dependence on external funding sources for large-scale project implementation. • Slow development of domestic hydrogen market demand.

Furthermore, Albania's commitment to EU Green Deal objectives reinforces its position in the European clean energy transition. The country has already exceeded its National Renewable Energy Action Plan [6] target of 38% renewable energy in final consumption by 2020, reaching 45%. This alignment with European sustainability policies enhances Albania's ability to attract investments, access EU funding, and develop a competitive hydrogen economy.

A key strategic asset is Albania's existing natural gas infrastructure, particularly the Trans Adriatic Pipeline (TAP), which became operational in 2020. The role of TAP and Albania's natural gas infrastructure is more than peripheral: it represents a fully operational, large-scale asset that can accommodate multi-megawatt hydrogen systems. In contrast to electrolysis, which still requires substantial investment in electrolyzer deployment and renewable integration, SMR is immediately compatible with existing infrastructure, making it the most infrastructure-ready pathway in the near term, as evidenced by techno-economic assessments highlighting its lower capital intensity and current integration within hydrogen supply chains [57,58]. However, this readiness comes at the expense of higher carbon emissions, underscoring the need for CCS integration if SMR is to align with EU decarbonization policies. Retrofitting TAP for hydrogen blending and eventual transport remains a strategic opportunity, but requires further feasibility studies on technical adaptation, safety standards, and regulatory approval to ensure cross-border compatibility [59].

Additionally, Albania's geographical proximity to EU markets positions it as a potential hydrogen exporter, particularly to Italy, Greece, and Central Europe, which have growing hydrogen demand.

Finally, the potential for off-grid renewable hydrogen production is another notable advantage. Direct connections to solar or wind farms for hydrogen electrolysis can bypass grid-related costs and inefficiencies, making production more competitive [60]. This approach supports decentralized hydrogen production, enhancing energy resilience and reducing reliance on grid electricity pricing fluctuations.

3.2.2. Weaknesses

Albania faces several barriers that hinder the development of a competitive hydrogen economy. In general, the scalability of green hydrogen production is challenged by a lack of infrastructure, energy losses, high power consumption, and significant costs across the value chain [61]. Prominent obstacles for hydrogen adoption noted in the literature include a lack of government support and infrastructure, high investment and operating costs, regulatory and standards gaps, difficulties in scaling to industrial levels, and competition from alternative low-carbon technologies [62,63].

One of the primary challenges is high hydrogen production costs, driven by elevated electricity prices [64], making green hydrogen less competitive compared to other energy sources. While reducing electricity costs could improve competitiveness, high upfront capital requirements—particularly for electrolysis facilities—remain a major obstacle [65]. As of 2023, according to European Hydrogen Observatory [13] the Alkaline electrolyzers (1666 EUR/kW) are cheaper than PEM electrolyzers (1970 EUR/kW), yet their costs remain higher than solar PV and wind projects, making hydrogen a less attractive investment. Additionally, long-term business planning remains a challenge in Albania. The lack of an entrepreneurial mindset oriented toward long-term investment continues to promote short-term decision-making, ultimately deterring capital-intensive initiatives like hydrogen production—projects that require patient capital, sustained policy backing, and a high tolerance for delayed returns [66]. This pattern reflects broader entrepreneurial behavior observed by Debrulle et al. [67], who found that extrinsically motivated entrepreneurs tend to prioritize short-term financial outcomes, potentially limiting engagement with long-horizon investments like hydrogen. Conversely, intrinsic motivation supports long-term strategic planning, but combining both motivations may create internal financial dilemmas that undermine decision-making in early project stages.

Investor perceptions reinforce this dynamic: recent research [68] shows that although investor sentiment toward hydrogen—particularly green hydrogen and renewable energy—is generally neutral to positive, actual investment decisions are highly dependent on the availability of financial support and favorable electricity prices. In Finland, for instance, most companies view investment aid as a prerequisite for moving forward with hydrogen projects, highlighting the difficulty in securing funding and navigating permitting processes. Similar barriers likely apply in Albania, where despite hydrogen's inclusion in the Energy Plan 2024–2030, no financial incentives (e.g., subsidies, grants, or tax breaks) are currently in place to support large-scale deployment. Moreover, limited political attention and delayed policy integration further hinder progress. Albania's National Energy Strategy (2018–2030) primarily focuses on energy diversification and renewable expansion but lacks explicit provisions for hydrogen-related infrastructure, such as fuel cells, electrolyzers, and hydrogen storage. Role of government support in green hydrogen storage remains crucial [69].

A major constraint is the lack of distribution and storage infrastructure, which severely limits hydrogen adoption [61,63]. These infrastructure gaps—particularly the absence of established hydrogen pipelines, refueling stations, and large-scale storage facilities—remain the most critical challenge to market expansion. Additionally, uncertain demand and slow market development pose risks, as Albania's industrial sector—key to hydrogen uptake—is underdeveloped compared to other European countries. The manufacturing sector, which includes food processing, textiles, footwear, and construction materials, is less advanced than regional peers, reducing potential industrial hydrogen demand. Another critical weakness is the lack of knowledge and expertise in hydrogen technologies. The Western Balkans faces a significant skills gap in transitioning to green jobs, as highlighted by the Joint Research Centre (JRC) report [70]. This challenge is exacerbated by the absence of specialized training programs, particularly for reskilling workers from fossil fuel industries to emerging green sectors. Studies by Aliu et al. [71] show that Albania's Vocational Education and Training (VET) programs and system fail to equip students with the necessary technical skills for hydrogen and fuel cells, creating a workforce gap that slows industry adoption. The 2023 Gallup International GmbH survey [72] highlights the urgent need for public awareness campaigns to improve understanding and acceptance of hydrogen technologies. Overcoming misconceptions and knowledge gaps is essential for fostering adoption and building investor confidence. Additionally, strengthening research and development (R&D) capacity will be crucial for enhancing Albania's expertise and technological innovation in the hydrogen sector. While reducing electricity costs alone will not make green hydrogen competitive, targeted policy support, financial incentives, infrastructure investment, and workforce development are critical. As noted by industry experts [73], a robust support ecosystem is essential to close the hydrogen cost gap and encourage investment throughout the hydrogen value chain. The most pressing challenge remains the lack of distribution and storage infrastructure, which significantly limits Albania's hydrogen market expansion. Addressing these weaknesses through strategic planning, investment, and regulatory improvements will be key to Albania's success in hydrogen development.

3.2.3. Opportunities

Albania has several opportunities that could support the growth of its hydrogen economy, ranging from energy diversification and access to international funding to technological advancements and export potential. One of the key opportunities is energy diversification, as hydrogen can reduce reliance on hydropower, which currently dominates Albania's energy mix, accounting for 98.98% of total electricity generation in 2023 (8,705,910 MWh out of 8,795,634 MWh). However, hydropower is susceptible to seasonal variations, making renewable energy diversification crucial for long-term energy security. Albania's solar PV capacity was only 3 MW in 2019, but projections for 2030 [55] estimate a technical potential of 2378 MW and an economic potential of 1074 MW, highlighting significant growth opportunities. Similarly, wind energy, with no installed capacity in 2019, has a technical potential of 7483 MW and an economic potential of 616 MW by 2030. Expanding hydrogen production using solar and wind power would both enhance energy security and help integrate a greater amount of variable renewable energy sources into the grid, which would, in turn, reduce the nation's reliance on imported fossil fuels. Additionally, green hydrogen can serve as a long-term energy storage solution, improving grid stability and reducing curtailment of excess solar and wind energy [74]. For Albania's growing renewable energy sector, this could be highly beneficial, as hydrogen can function as a bridge between the intermittent nature of renewable generation and a continuous energy demand.

Albania also has potential access to significant EU funds and grants from institutions such as the KfW, EBRD, and World Bank, which are actively supporting green hydrogen projects across Europe. Through the Western Balkans Investment Framework [75], between 2008 and 2024, Albania received €472.4 million in grants, which includes €410.2 million in investment grants and €62.2 million in technical assistance. Additionally, in 2025, Albania is set to receive €657 million from the EU through a loan agreement, which could be strategically allocated to accelerate the development of hydrogen infrastructure, research, and policy frameworks. By leveraging these financial resources, Albania can bridge investment gaps, enhance its energy transition efforts, and position itself competitively in the European hydrogen market. Strengthening partnerships with European energy stakeholders could also help attract private sector investments, fostering long-term industry development. The EU is driving hydrogen development through various industrial, funding, and research and innovation programs, such as the Clean Hydrogen Partnership, the European Clean Hydrogen Alliance, and the Hydrogen Public Funding Compass.

Growth in the hydrogen and fuel cell industries is expected to create a wide variety of new jobs, requiring diverse skills and offering different levels of earnings across numerous sectors [76]. Some of these jobs will be substituted from existing industries, while others will be newly created. According to Leguijt et al. [77] the average number of jobs per gigawatt (GW) of installed electrolysis capacity is 2.55 (1.0–4.1) in 2030, 10.6 (2.4–18.8) in 2040, and 18.55 (3.7–33.4) in 2050.

Another major opportunity is the rapid decline in hydrogen production costs, particularly for electrolyzers, fuel cells, and storage systems. Electrolyzers costs alone are expected to decrease by over 40% by 2030 and up to 80% in the long term [78], driven by larger production facilities, design standardization and efficiency improvements. According to Zun and McLlelane et al. [79], an optimistic scenario could see electrolyzer capital costs drop to \$88/kW for alkaline and \$60/kW for PEM electrolysis by 2050. Even in a pessimistic scenario, costs are still expected to decline to \$388/kW for alkaline and \$286/kW for PEM electrolysis, with PEM technology projected to dominate the market. Consequently, green hydrogen production costs in regions with ideal renewable resources might decrease to as little as €5/kg, which would make it highly competitive with fossil fuel-based hydrogen. These anticipated cost trends are expected to substantially lower Albania's current high LCOH, thereby making hydrogen projects more financially appealing over time.

In recent decades, natural gas has played an increasingly significant role in Albania's energy landscape, experiencing a remarkable 323% increase between 2000 and 2022 [80]. This highlights the growing role of gas infrastructure, which could be leveraged for hydrogen transportation and storage. Albania's existing natural gas infrastructure, particularly the Trans Adriatic Pipeline (TAP), presents a strategic opportunity for low-cost hydrogen production through SMR. TAP provides direct access to natural gas resources, enabling cost-effective hydrogen production while leveraging existing infrastructure to minimize capital investment in new supply chains.

With Europe accelerating its hydrogen transition, Albania is strategically located to supply green hydrogen to EU markets, particularly to Italy, Greece, and Germany, where demand is expected to surge significantly by 2030. To capitalize on this opportunity, Albania will need to develop dedicated hydrogen infrastructure, secure long-term power purchase agreements (PPAs) with European buyers, and align its hydrogen production strategy with EU regulatory standards.

3.2.4. Threats

While transitioning to a hydrogen economy presents significant opportunities for Albania, several challenges could hinder its development. One major threat is competition from other renewable technologies, particularly solar power combined with battery storage, which is becoming increasingly cost-competitive and may outperform hydrogen in certain applications. High production costs and economic viability remain significant barriers, as green hydrogen is still more expensive than fossil fuels and other renewable energy sources.

Additionally, public concerns about hydrogen safety—despite advancements in safety protocols and technologies—could slow adoption and regulatory approvals. Recent research indicates a strong preference for hydrogen produced from renewable sources, while hydrogen derived from non-renewable sources tends to be rejected by the market [80]. The greatest safety concerns are not about hydrogen's end use in transport but rather its storage and transport infrastructure [81]. In this context, concerns about hydrogen safety are closely linked to trust—an issue that extends beyond simple communication strategies [82]. In Albania, where trust in the local industry and its ability to adhere to safety standards is relatively low, safety concerns are particularly pronounced. Addressing these concerns will require not only technological improvements but also stronger regulatory oversight and transparent engagement with the public.

Furthermore, regional competition from neighboring countries with more developed hydrogen infrastructure and stronger policy incentives could limit Albania's ability to attract investment and establish itself as a hydrogen hub. Lastly, Albania's reliance on external funding for hydrogen projects introduces uncertainty, as delays or reductions in international financial support could stall progress.

3.2.5. Hydrogen Market SWOT: Albania vs. Global Case Studies

To contextualize Albania's hydrogen market readiness, this study compares national SWOT findings with those from international case studies. Existing SWOT analyses on hydrogen economies have been conducted worldwide [28–35] highlighting diverse strengths, weaknesses, opportunities, and threats shaping hydrogen market development across different socio-economic and policy contexts. Key SWOT findings for these countries are summarized in Table 3 below. These studies highlight the diverse strengths, weaknesses, opportunities, and threats influencing hydrogen economies worldwide. For example, Ren et al. [28] identified China's strengths as abundant resources and potential, weaknesses as cost and technology, opportunities as government support and social acceptance, and threats as competition and uncertain market potential. Similarly, Bednarczyk et al. [33] found that Poland has strengths in policy support and growing generation capacity, weaknesses in limited investment, fossil fuel reliance, and infrastructure gaps, opportunities in EU market development and funding, and threats from policy delays, rising energy costs, and competition. Simões and Santos [35] analyzed the green hydrogen market, noting strengths in environmental benefits and government support, weaknesses in production costs and technology immaturity, opportunities in technology advances and cost reductions, and threats from inefficient policies and lack of standards. Khan and Al-Ghamdi [34] explored the hydrogen economy in Middle Eastern nations, including Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates. Their findings highlighted strengths in available resources and strategic vision, weaknesses in production costs and infrastructure, opportunities stemming from global decarbonization efforts and increasing demand, and threats from international competition and market dependencies. Bayssi et al. [30] indicated that North African countries have strengths in renewable resources and location, weaknesses in regulations and infrastructure, opportunities in government commitment and collaborations, and threats in market competition and price fluctuations.

de Oliveira et al. [31] determined that Brazil has strengths in renewable resources and infrastructure, weaknesses in production costs and infrastructure gaps, opportunities in global demand and government support, and threats in competition and economic volatility. To analyze the hydrogen economy in Türkiye, Furuncu [32] conducted a study using a PESTEL and SWOT analysis. Turkey's hydrogen economy has strengths in its developing policy framework and increasing renewable energy integration. Weaknesses include infrastructure limitations and a dependence on energy imports. Opportunities exist in its strategic location for exports and rising government support, while threats come from policy uncertainties and regional competition.

Table 3. Comparative SWOT Analysis of Hydrogen economies across selected countries.

Country/Region	Strengths	Weaknesses	Opportunities	Threats
Albania	Strong Renewable Energy Base a& Infrastructure, Increasing government recognition of hydrogen Proximity to EU markets	High hydrogen production costs, lack of storage and distribution infrastructure, limited financial incentives, regulatory gaps, lack of expertise	Energy diversification, access to EU and international funding, job creation, declining electrolysis costs, potential for green hydrogen exports	Competition from solar + battery storage, high production costs, regional competition, dependence on external funding, slow market development
China (Ren et al. [28])	Abundant resources, strong industrial potential	High costs, technological gaps	Government support, growing social acceptance of hydrogen	Market competition, uncertain long-term economic viability
Poland (Bednarczyk et al. [33])	Strong policy support, growing hydrogen generation capacity	Limited investment, reliance on fossil fuels, infrastructure gaps	EU hydrogen market development, access to EU funding	Policy delays, rising energy costs, competition from other energy sources
Iran (Rahimirad and Sahabadi [24])	Large natural gas reserves, potential for hydrogen production	Lack of investment, economic sanctions, limited technology transfer	Export opportunities, regional energy market potential	Geopolitical instability, sanctions affecting market growth
Gulf Countries (Khan and Al-Ghamdi [34])	Abundant natural resources, strategic vision for energy transition	High production costs for green hydrogen, infrastructure limitations	Global decarbonization efforts, increasing hydrogen demand	Global competition, reliance on external markets
North Africa (Bayssi et al. [30])	Abundant renewable resources, strategic geographic position for exports	Weak regulatory frameworks, underdeveloped infrastructure	Government commitment, international collaborations for hydrogen projects	Market competition, fluctuating energy prices
Brazil (de Oliviera et al. [31])	Large renewable energy capacity, existing energy infrastructure	High production costs, infrastructure development challenges	Growing global hydrogen demand, government incentives	Competition from other renewables, economic volatility
Turkey (Furuncu [32])	Growing hydrogen policy framework, increasing renewable energy integration	Infrastructure limitations, dependence on energy imports	Strategic location for hydrogen exports, increasing government focus on hydrogen projects	Policy uncertainties, competition from regional energy markets

The SWOT-related studies reveal several key comparative insights:

- Strengths: Growing policy support and government recognition are a primary strength across countries. Many also benefit from abundant renewable energy resources (e.g., Albania, China, North Africa, Brazil) and existing energy infrastructure (e.g., Albania).

- Weaknesses: High hydrogen production costs and infrastructure gaps, particularly in storage and distribution, are common weaknesses. Limitations in investment, incentives, regulations, and expertise are also prevalent.
- Opportunities: Energy diversification and decarbonization are major opportunities. Declining electrolysis costs and access to funding mechanisms (e.g., EU funding) are also significant.
- Threats: Competition from other renewable energy technologies, policy uncertainties or delays, regulatory gaps, and slow market development are common threats.

The literature review highlights that high production costs and infrastructure limitations are recurring challenges. Hydrogen export potential is a significant opportunity for many countries, with Brazil, North Africa, and the Gulf states primarily targeting global markets, while Albania and Poland focus on EU funding. Albania's EU market access provides a strategic advantage, similar to Poland and Turkey. Additionally, competition from alternative renewable technologies, economic uncertainties, and policy delays present challenges for all nations transitioning to a hydrogen economy.

4. Conclusions

Global interest is rising in hydrogen as one of the solutions to the energy transition. Albania has faced significant energy challenges over the past 20 years, including reliance on hydropower and energy imports, highlighting the need for innovative and diversified energy sources such as hydrogen to enhance security and sustainability. However, hydrogen is a costly energy carrier that requires substantial infrastructure, regulatory frameworks, and financial incentives to become viable. This study assessed the techno-economic feasibility and strategic potential of hydrogen in Albania through a comparative analysis of production pathways and a SWOT framework. The results show that green hydrogen holds strong strategic potential, leveraging Albania's abundant renewable resources—particularly wind and solar—and its geographical proximity to EU markets. The SWOT analysis identifies major strengths, including a high share of renewables in the electricity mix, existing natural gas infrastructure, and alignment with EU Green Deal objectives; opportunities such as access to EU and international funding, declining costs of electrolysis and storage technologies, and potential for pipeline repurposing; but also significant weaknesses, notably high production costs, limited technical expertise, and the absence of dedicated hydrogen infrastructure; and threats, including competition from alternative renewable solutions, public safety concerns, and dependence on external funding. From a cost perspective, renewable-powered electrolysis currently produces hydrogen at 7.66–8.76 €/kg H_2—above EU averages—due to high electricity prices and limited electrolyzer deployment. In contrast, steam methane reforming (SMR) delivers lower costs (3.45 €/kg H_2), but at the expense of a high carbon footprint (~9–12 kg CO_2-eq/kg H_2). Incorporating carbon capture and storage (SMR + CCS) reduces emissions significantly, but increases costs to ~4.74 €/kg H_2. Given Albania's TAP infrastructure, SMR + CCS could serve as a transitional option if supported by carbon pricing and suitable storage facilities, but long-term competitiveness will depend on alignment with EU decarbonization policies. Environmental results reinforce this trade-off: grid-based electrolysis achieves very low GWP due to hydropower dominance, but also high-water-scarcity impacts; solar and wind electrolysis balance low emissions with reduced water footprint; SMR shows the lowest water footprint but the highest GHG burden. These insights underscore the need for integrated climate–water strategies.

The combined interpretation of the techno-economic, environmental, and strategic assessments provides a clear roadmap for Albania's hydrogen future. The LCOH results establish the cost baseline, the LCA reveals critical environmental trade-offs, and the SWOT framework situates both within Albania's policy, infrastructure, and market context. Together, they show that while fossil-based pathways remain cost-attractive in the short term, only renewable-powered electrolysis ensures long-term compatibility with EU decarbonization goals. This integrated perspective yields actionable conclusions: policymakers should prioritize renewable-based electrolysis, supported by targeted incentives to lower costs, while simultaneously addressing infrastructure gaps and building investor confidence through stable regulatory frameworks. Large-scale, dedicated renewable energy plants—such as the Karavasta solar park—could provide a stable, low-cost electricity supply, making competitive green hydrogen production possible. Realizing this vision will require coordinated action: accelerating renewable capacity expansion, scaling electrolyzer deployment, introducing clear regulatory and incentive frameworks, and developing technical expertise through targeted training. With the right strategic investments and policy measures, Albania can position itself as a regional hub for sustainable hydrogen production, capitalizing on both domestic needs and export opportunities.

Future research should explore scenario-based sensitivity analysis under Balkan electricity market volatility, financing conditions in higher-risk environments, and quantitative validation of SWOT factors (e.g., expert surveys, multi-criteria analysis). In addition, research on public acceptance and socio-economic impacts will be critical for ensuring the long-term competitiveness and sustainability of Albania's hydrogen economy.

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Abbreviations

The following abbreviations are used in this manuscript:

CAPEX	Capital Expenditure
CCS	Carbon capture and storage
EBRD	European Bank for Reconstruction and Development
EU	European Union
GWP	Global Warming Potential
KfW	Kreditanstalt für Wiederaufbau (German Development Bank)
LCA	Life Cycle Assessment

LCOH	Levelized Cost of Hydrogen
OPEX	Operating Expenditure
PEM	Proton exchange membrane electrolyzer
PV	Photovoltaic
SMR	Steam Methane Reforming
SWOT	Strengths, Weaknesses, Opportunities, and Threats
TAP	Trans Adriatic Pipeline
VET	Vocational Education and Training
WB	Western Balkans
WULCA	Water Use in Life Cycle Assessment (LCA)

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