Economic Viability of Green Hydrogen Production in European Energy Systems

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Abstract— **As the second round of European Hydrogen Bank auctions progresses, understanding bid prices and their economic impact is essential. This study is an approach to comprehend unexpectedly large differences in bids from the first auction and evaluate renewable hydrogen production in Austria, Portugal, and Spain. The simulation-based assessment of Levelized Costs of Hydrogen and economic performance highlights that higher PV and wind energy yields in Portugal and Spain create advantageous conditions for auction participation, whereas Austrian projects require national funding to be competitive. Austria's 400 million EUR allocation under the 'Auction-as-a-Service' scheme could facilitate 58 kt of renewable hydrogen production, while the same amount could support the production of 105 kt in Spain. Depending on the hydrogen sales price, projects operate at a cost-recovery level and are only marginally profitable without funding, emphasizing the need for tailored support strategies to ensure the competitiveness of hydrogen production across Europe.**

Index Terms-- **Hydrogen, Levelized Cost of Hydrogen, Return on Investment, European Hydrogen Bank**

I. INTRODUCTION

The integration and utilization of hydrogen in the energy system is a critical component of the energy transition, essential to achieving decarbonization goals and mitigating climate change [1,2]. To meet the renewable gas quotas and CO_2 emission reduction targets outlined in European and national strategies [3–6], a significant ramp-up in renewable energy and green hydrogen production via electrolysis is required [7]. The RepowerEU plan sets the target of **10 million tonnes of annual domestic production** of renewable hydrogen within the EU as well as the same amount of imports [8]. As of 2023, less than 1 % of the production was low-emission hydrogen, with the vast majority of demand being supplied by fossil-based hydrogen [9].

In a world undergoing a transformative shift toward a renewable-powered society, the pace of green hydrogen production must accelerate. In 2023 less than **10 % of the announced clean hydrogen investments through 2030 have reached a final investment decision (FID)** [10], highlighting persistent hurdles project developers must navigate. These include the necessity of long-term offtake agreements, regulatory uncertainties, as well as the need for mitigating the risk of investments [11,12].

These challenges can be addressed via robust support and funding mechanisms, one example initiative being the European Hydrogen Bank's (EHB) auction-based funding scheme [13]. These operational expenditure (OpEx) grants, awarded through regular auctions, are designed to incentivize green hydrogen production by offering financial support for every kilogram of produced renewable hydrogen over a 10-year period, while fulfilling the requirements for green hydrogen production stated in the regulation of the Renewable Energy Directive (RED) II [14]. The results of the first auction, announced in 2024, saw the acceptance of seven projects, primarily located in regions with high renewable energy potential, including Spain, Portugal, Finland, and Norway [15]. This geographic distribution underscores a key challenge: projects in countries with lower renewable energy yields may face economic disadvantages in producing green hydrogen [16–19]. Within a future European-wide hydrogen network facilitated by the Hydrogen Backbone [20], this raises concerns on the competitiveness of such locations. Concentrating renewable hydrogen production in a few locations also conflicts with the increasingly decentralized nature of renewable electricity generation, due to necessary substantial investments in both electricity and gas grid expansion. To address this challenge, future studies will explore optimized combinations of renewable energy sources—including wind, PV, and hydropower—along with the required investments in grid infrastructure.

The economic feasibility of green hydrogen projects is not only influenced by renewable energy potential but also by the characteristics of country-specific energy systems and regional investment risks. Variations in energy prices, grid fees, and market structures across Europe can significantly impact production costs and competitiveness [21]. Additionally, regional investment risks, often captured by the weighted average cost of capital (WACC), play a crucial role as higher WACC values, typically associated with regions facing economic or political uncertainties, can substantially increase

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the cost of financing projects and reduce return on investment (ROI).

This study explores the economic disparities in green hydrogen production costs across different European regions and evaluates the extent to which country-specific funding schemes could level the playing field. Specifically, it investigates how such incentives must be structured to achieve equivalent economic viability, measured in terms of return on investment. Using a comparative analysis of green hydrogen production in Portugal, Spain, and Austria, the study aims to address the following questions:

- How do regional disparities impact hydrogen production costs, and to what extent can national subsidies mitigate these differences to reach equal ROIs?
- In which range do variations in key economic and technical parameters influence the return on investment (ROI) in hydrogen production?

By addressing these questions, the study contributes to the ongoing discourse on optimizing green hydrogen production and fostering a competitive and equitable hydrogen market across Europe.

II. METHODOLOGY

To comprehensively analyze the complex challenges of green hydrogen production in accordance with RED II within national energy systems, we developed the **Hydra App**. This fast and easy-to-use tool is based on the MATLAB/Simulink library described in [22–24]. The assessment of the technical and economic viability of hydrogen production sites through the Levelized Cost of Hydrogen (LCOH) is based on regional renewable energy profiles, country-specific energy grid prices and economic boundary conditions. By defining equal target ROIs for each project, necessary national fundings at each location are subsequently determined. To evaluate the impact of key economic and technical parameters, a sensitivity analysis is conducted to assess their influence on the ROI.

The location-specific renewable energy-profiles are generated in the pre-processing, along with the acquisition of the country-specific grid fees and investment risks in the form of the Weighted Average Cost of Capital (WACC). The available renewable energy at every timestep is used to produce hydrogen in the electrolyzer according to a normed efficiency curve. The post-processing cost calculations are based on [25], resulting in location-dependent information for the Levelized Cost of Hydrogen. This enables the subsequent determination of the necessary national subsidies for comparable return on investments across Europe.

A. Regional Renewable Energy Profiles and Grid Fees

The considered production locations in this study are two of the winning projects of the first EHB auction: project MP2X in Sines (Portugal) and project Catalina in Aragon (Spain), as well as the comparison location Podersdorf in Austria. The location-specific renewable energy profiles have been generated using data from PVGIS [26] as well as the IRENA database [27] as described in [22]. In order to eliminate the possible influence of the selected locations on the LCOH results, the ENTSO-E mean production profiles for PV- and wind power generation have been analyzed for each country as a subsequent step [28], whereas the Austrian profile has been scaled to the national mean energy yield from [29] due to an disproportionately low value in the ENTSO-E data.

The country-specific grid fees are based on Eurostat data for non-household consumers (excl VAT) [30]. To account for subsidies and price-dampening effects active in 2023, pre-crisis values from 2019 were adjusted using national inflation rates. [30]. Investment risks are reflected by applying the 2023 WACC of national electricity system operators [31–33]. The rated capacities of PV and wind systems align with the EHB MP2X and Catalina project specifications [34]. For the Austrian reference case, equal PV and wind capacities with a 2:1 renewable-to-electrolyzer power ratio were used, following the favorable outcomes identified in [22]. TABLE I. includes the relevant location-specific simulation parameters.

TABLE I. LOCATION-SPECIFIC SIMULATION PARAMETERS

Parameter	**Location-specific Simulation Parameters**		
	Region	***Value***	***Unit***
Energy yield PV [26,28]	Podersdorf, Austria	1224	kWh / kWp
	Austria – Mean [29]	1000	
	Sines, Portugal	1665	
	Portugal - Mean	2412	
	Aragon, Spain	1673	
	Spain - Mean	1379	
Energy yield Wind [26–28]	Podersdorf, Austria	2106	kWh / kWp
	Austria - Mean	2314	
	Sines, Portugal	2403	
	Portugal - Mean	2798	
	Aragon, Spain	2107	
	Spain - Mean	2083	
Grid fees [30]	Austria	116.32	€ / MWh
	Portugal	135.68	
	Spain	99.8	
Inflation 2019 – 2023 [30]	Austria	23.75	%
	Portugal	15.08	
	Spain	15.92	
WACC [31–33]	Austria	4.88	%
	Portugal	4.95	
	Spain	5.58	
PV power [34]	Austria	500	MW
	Portugal	633	
	Spain	571	
Wind power [34]	Austria	500	MW
	Portugal	375	
	Spain	614	

B. Simulation Model

The electrolyzer power is defined at 500 MW, as stated in the EHB project descriptions [34], with the operating strategy designed to maximize the hydrogen production. Between the minimum and maximum power limits of the electrolyzer, the available renewable power is utilized for hydrogen production while accounting for the system's power gradients. Any renewable power exceeding the maximum capacity of the electrolyzer is discarded, as renewable grid feed-in is not considered in this study. The same accounts for renewable input powers below the minimum operational threshold of the electrolysis system. The technical characteristics of the electrolyzer are shown in TABLE II.

TABLE II. TECHNICAL CHARACTERISTICS OF THE ELECTROLYZER

Electrolyzer parameter	***Value***	***Unit***
Nominal power P_{Ely}	500	MW
Maximum system efficiency in best operating point (based on LHV)	65	%
Minimum power	5	% of P_{Ely}
Power gradient over time	± 10	% of P_{Ely}/s

C. *Economic Evaluation using LCOH and ROI*

The economic evaluation is conducted by calculating the net present values (NPV) of all cost components in accordance with standard [25]. TABLE III. depicts the economic parameters used in the simulation study.

TABLE III. ECONOMIC SIMULATION PARAMETERS

	Economic simulation parameter	***Value***	***Unit***
General	Observation period N	10	Years
	Installation costs (relative to initial invest of electrolyser)	50	%
Electrolyzer	Initial investment	949	EUR/kW
	Replacement invest (stack replacement)	430	EUR/kW
	Annual operational costs (relative to initial invest)	5	%
	Price increase rate	-3.8	%/year
	Operating lifetime stack	60,000	Hours
	Operating lifetime electrolysis system	20	Years
PV	Initial investment	883	EUR/kW
	Annual operational costs	2.5	%
Wind	Initial investment	1700	EUR/kW
	Annual operational costs	4	%

The investment (CapEx) and operational (OpEx) NPVs are determined based on the WACC as described in [23] for the imputed interest rate. Storage costs are hereby not included, assuming a project location with nearby connection to the European Hydrogen Backbone which meets all technical requirements. This also ensures comparability of the project locations regarding their economic viability. The LCOH for each of the analyzed configurations is calculated with the annually produced hydrogen $m_{H_{2_n}}$ during the observation period N, the cost components $CapEx_{NPV}$, $OpEx_{NPV}$, as well as the regional WACC, using (1).

$$\mathrm{LCOH} = \frac{\mathrm{CapEx_{NPV}} + \mathrm{OpEx_{NPV}}}{\sum_{n=0}^{N} m_{H_{2_n}} \cdot \left(\frac{1}{1+\mathrm{WACC}}\right)^{n}} \tag{1}$$

To compare project profitability across regions, the annualized ROI is calculated in percent using (2) and (3), with the observation period N set to the 10-year funding duration of the EHB. This ensures that the annual ROI over the complete system lifetime is not financed through the 10-year funding period, which would lead to considerably higher funding needs.

The analysis considers three scenarios: Scenario 1 uses location-specific PV and wind profiles to assess the individual EHB sites, while Scenarios 2 and 3 apply national average profiles to represent typical conditions—relevant for estimating general funding needs. In contrast to Scenario 2, Scenario 3 includes grid fees in case of a more distant renewable energy source. It is assumed that the hydrogen sales price is equal for all project locations, facilitated by a common European market and hydrogen transport via the European Hydrogen Backbone.

$$\mathrm{ROI} = \frac{\mathrm{Revenue_{NPV}} - (\mathrm{CapEx_{NPV}} + \mathrm{OpEx_{NPV}})}{\mathrm{CapEx_{NPV}}} \tag{2}$$

$$\text{Annualized ROI} = \left[(1+\mathrm{ROI})^{(1/N)} - 1\right] \cdot 100\ \% \tag{3}$$

Comparable profitability for each project location is ensured by determining equal annualized ROIs. For the following analysis an annual ROI of 5 % has been assumed to calculate the funding needs in Euro per kilogram over a period of 10 years via (4), incorporating interest calculations. The required funding is derived based on the additional revenues needed to achieve the target return on investment in each scenario.

$$\text{Funding needs} = \frac{\text{Additional Revenue}_{\mathrm{NPV}}}{m_{H_{2_n}}} \cdot \frac{\frac{1}{1+\mathrm{WACC}} - 1}{\left(\frac{1}{1+\mathrm{WACC}}\right)^{N} - 1} \tag{4}$$

III. RESULTS

A. *Effect of Energy Yields on Levelized Cost of Hydrogen and H_2 Production*

Fig. 1 presents the LCOH results for the three analyzed scenarios in Austria, Portugal, and Spain, along with the respective annual renewable hydrogen production. Scenario 1 utilizes location-specific PV and wind energy profiles, while Scenario 2 and Scenario 3 depict results based on country-mean profiles, with direct electrolyzer connection and grid-based renewable energy supply (Offsite), respectively.

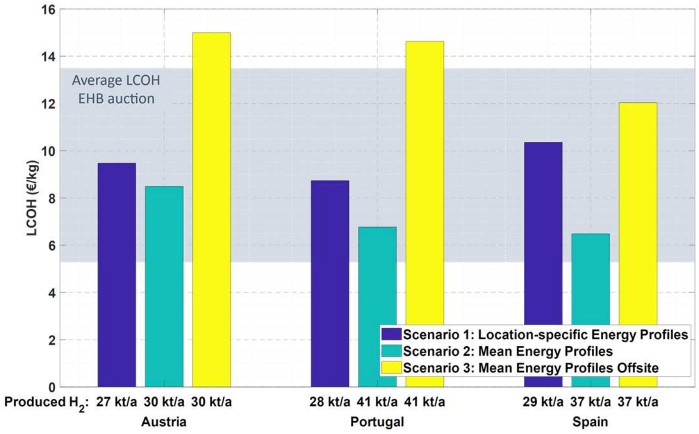

Figure 1: Resulting LCOH for the analyzed countries in different scenarios, including the annually produced amount of renewable hydrogen

The following analysis focuses on Scenario 2 to avoid biases caused by the selection of a specific location with lower energy yields. The resulting hydrogen production capacities are hereby more consistent with the EHB project reports. Additionally, country-mean energy profiles are used to assess the benefits of spatially distributed renewable energy generation for hydrogen production. While this approach enhances energy supply reliability, it also introduces grid fees, which must be considered in the overall economic assessment.

The impact of renewable energy yields on LCOH is evident when comparing the countries and the location-specific profiles against the mean-profile approach. These scenarios are based on the premise that renewable energy systems in high-yield locations offer economic advantages. However, when grid supply is required, as in the Offsite scenario, **energy grid fees introduce additional costs that may surpass location-based benefits**, as illustrated in Fig. 1.

The majority of the results fall within the LCOH range observed in the EHB auction results (5.3 to 13.5 EUR/kg) [34]. In Austria, an LCOH of 8.49 EUR/kg is achieved using the mean energy profile, compared to 9.48 EUR/kg at the specific location of Podersdorf. For the MP2X (Portugal) and Catalina (Spain) projects, the LCOH values are 8.73 EUR/kg and 10.36 EUR/kg with location-specific energy profiles, while the ENTSO-E mean profiles lead to 6.77 EUR/kg and 6.48 EUR/kg, respectively. The relatively high values are driven by the 10-year observation period to correspond to the time span of the EHB funding.

Based on the pipeline transport costs in [22], a 0.167 EUR/kg surcharge on the sales price would be required per 1000 km transport distance. Hydrogen transport from Portugal or Spain to Central Europe, spanning a distance of 2,000 to 3,000 km leads to **additional transport costs** of 0.33 to 0.50 EUR/kg, **which partially offsets the disadvantage of domestic production** in Austria for off-takers in the region. Transport via trailers is not economically viable for the hereby analyzed hydrogen quantities and international transport. Maritime transport from e.g. seaside ports in Spain or Portugal to Central Europe is technically feasible, but according to [22] not cost-effective over these distances.

In general, the advantageous renewable energy yields in Portugal and Spain induce higher annual renewable hydrogen production rates and lower LCOH compared to the reference case in Austria. However, the simulated hydrogen output for the Portuguese and Spanish EHB projects falls short of the targeted production levels stated in the EHB reports, with a deficit of 10.6 kt/year (511 kt over 10 years in Portugal and 480 kt in Spain [34]). Achieving these targets solely through the specified renewable sources would require significantly higher energy yields. This indicates that **future project strategies may involve additional grid supply** (provided the grid meets RED II renewable quota requirements [14]) or Power Purchase Agreements (PPAs) to further enhance renewable hydrogen production capacity.

For the subsequent analysis of economic profitability (measured via ROI), the results from Scenario 2 are used, which are based on the country-wide average renewable energy profile. This approach represents a spatial distribution of the generation plants and ensures that the findings are representative and applicable to generic locations within the country, rather than being limited to a single specific site.

B. Economic Viability Based on Hydrogen Market Prices

The EHB auction results indicate expected hydrogen sales prices of **5.67 EUR/kg** for industrial applications and **8.34 EUR/kg** for the mobility sector [35]. Assuming a common target ROI of **5 % per year**, the required funding per kilogram over a **10-year period** is calculated for each project, as shown in Fig. 2. Based on LCOH results, Austria displays significantly higher funding requirements compared to Portugal or Spain.

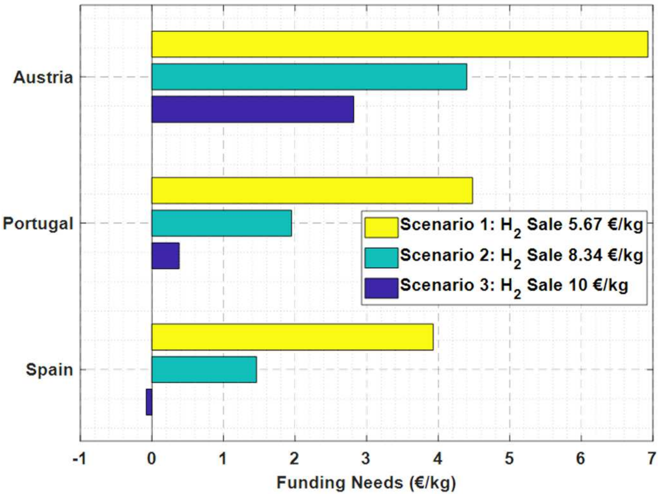

Figure 2: Funding needs in EUR/kg for a period of 10 years to achieve 5 % of annual ROI as a function of the hydrogen sales price

For hydrogen sold to the **industrial sector**, achieving the target ROI in Austria would require **6.93 EUR/kg** in funding over 10 years, while **4.48 EUR/kg** is needed in Portugal and **3.93 EUR/kg** in Spain. In the **mobility sector** scenario, funding needs range from **1.46 EUR/kg** in Spain to **4.40 EUR/kg** in Austria. Higher hydrogen sales prices reduce funding requirements at all locations, improving economic viability. However, only in the reference scenario, where a rather high sales price of **10 EUR/kg** is assumed, the project location in Spain reaches **5 % annual ROI** (-0.08 EUR/kg funding needs). In Portugal 0.38 EUR/kg and in Austria 2.82 EUR/kg funding are necessary.

Considering the allocated **0.48 EUR/kg** funding for the MP2X and Catalina projects, the **annual ROI** ranges from **-0.85 % to 3.27 %** for the Portuguese project (industry-to-mobility sales prices) and **-0.32 % to 3.84 %** for the Spanish project, offering economic viability only in the mobility scenario. This indicates that 5 % annual ROI cannot be achieved under probable hydrogen sales price conditions. Based on the hydrogen sales prices and auction bid prices, it can be expected that the hydrogen production infrastructure can be operated in a **cost-covering and marginally profitable** basis.

The comparison of the analyzed countries shows a clear disadvantage for the Austrian reference location in securing grants from the EHB auctions. Due to higher hydrogen production costs and funding requirements, Austrian projects need to submit higher bids to achieve comparable ROIs, reducing the likelihood of success in the auction process. In this case, **national funding programs** are necessary to mitigate the disadvantage and offset the higher LCOH. Such support mechanisms enable renewable hydrogen production facilities in countries like Austria to achieve economic returns comparable to those in higher energy yield regions.

Under the European Hydrogen Bank's 'Auctions-as-a-Service' scheme, Austria committed to allocate 400 million EUR from its national budget to support renewable hydrogen production [36]. In the industrial sales price scenario, this funding could enable the production of **58 kt of renewable hydrogen**. Spain will allocate between 280 and 400 million EUR [36], corresponding to the support of 73 to 105 kt of funded renewable hydrogen.

C. Sensitivity Analysis of Technical and Economic Factors on Return on Investment

Fig. 3 presents the sensitivity analysis of key technical and economic parameters affecting a project's ROI, using the Portuguese project with country-average energy profiles as the baseline (ROI: **0.78 %**). To isolate parameter effects without contortion of the EHB funding scheme, a 20-year observation period without funding is assumed for the base case, while sensitivities for funding amount and period use 0.48 €/kg and 10 years as a base.

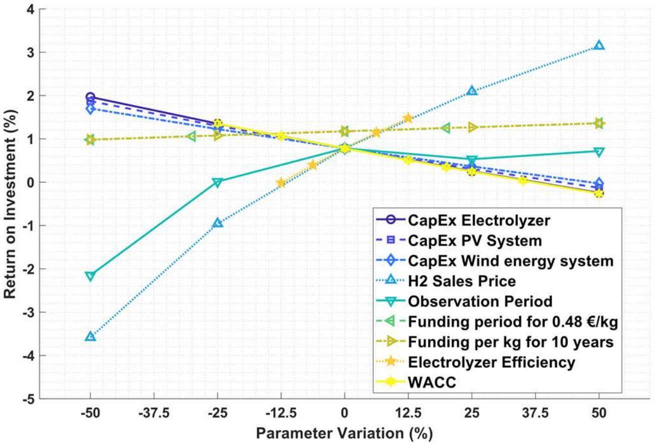

Figure 3: Sensitivity Analysis on ROI for Portuguese project

Among the analyzed parameters, the hydrogen sales price exerts the most significant impact on economic performance. A **25 % increase** in the base sales price of **5.67 EUR/kg** more than doubles the ROI to **2.09 %**. However, this effect is non-linear, with diminishing returns at larger price increases beyond the base case. The sensitivity analysis of the sales price also covers the depiction of the effects of **additional transport costs or revenues from CO_2 certificate trading**, which effectively reduce (through transport cost surcharges) or increase (via certificate sales) the realized sales price. In the same manner revenues from possible grid feed-in of surplus renewable energy can be considered.

Emission reductions of 10 to 13 kg CO_2-eq per kg renewable hydrogen, as stated in [37] relative to natural gas, could generate additional revenues of **1 to 1.3 EUR/kg** at a certificate value of **100 EUR/t CO_2**.

The investment costs of PV, wind, and electrolysis systems, as well as country-specific investment risks (WACC), show comparable impacts on ROI. Reductions in investment costs and risks improve economic performance, emphasizing the importance of technological advancements, cost reductions, and stable economic and political conditions. Additionally, the analysis demonstrates how **higher electrolyzer efficiencies** further enhance ROI, underscoring the value of efficiency improvements.

The ROI is also influenced by the observation period, as it determines the cumulative revenue and cost recovery over time. Consequently, the system's operation beyond the funding period plays a critical role in the overall economic performance of a project. External support mechanisms, such as the EHB funding scheme, represented through variations in funding amount and period, have a linear impact on ROI. Such measures are valuable in addressing initial cost barriers, such as offtake uncertainties and investment risks, thereby **supporting project feasibility during the early stages.**

IV. CONCLUSION

The analysis provides valuable insights into how different energy systems and markets shape the technical and economic performance of renewable hydrogen production. Regions like Portugal and Spain benefit from higher renewable energy yields, resulting in lower LCOH and increased hydrogen output compared to Austria. Despite these advantages, the simulated hydrogen output for the Portuguese and Spanish EHB projects remains below the targeted production levels, indicating the need for additional grid supply. However, the reliance on grid-based (Offsite) energy supply introduces additional network fees that can offset the economic advantages of high-energy-yield locations.

The economic feasibility analysis shows that a 5% annual ROI cannot be achieved under likely hydrogen sales price conditions. Instead, hydrogen production infrastructure is expected to operate at a cost-covering or marginally profitable level. Among the analyzed countries, Austria faces a clear disadvantage in securing EHB auction grants, as higher production costs necessitate higher bid prices, lowering the chances of success. To remain competitive, targeted funding programs are essential. Without such support, hydrogen projects in Central Europe, including Austria, will struggle to compete economically with lower-cost regions.

To bridge this gap, Austria has committed 400 million EUR under the 'Auction-as-a-Service' scheme, supporting 58 kt of renewable hydrogen production. In comparison, Spain's planned allocation of 280–400 million EUR could enable 73 to 105 kt of hydrogen production. National funding schemes play a critical role in developing a resilient EU-wide hydrogen supply, strengthening Europe's energy independence, and enhancing industrial stability.

Overall, the findings emphasize the need for a balanced approach that combines technological innovation, favorable market conditions and strategic funding mechanisms to ensure the economic success and scalability of renewable hydrogen projects across Europe.

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