Water-conscious and CO_2-Negative Hydrogen Production in the European Union

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***Abstract*— Achieving climate goals necessitates both significant emission reductions and large-scale carbon dioxide removal (CDR). This study explores the cost, technical potential and economic feasibility of integrating direct air capture (DAC) and storage with hydrogen production via electrolysis to simultaneously enable emission reductions and CDR. Utilizing a techno-economic optimization model, the performance of the coupled system is analyzed across the EU. Our analysis reveals the potential of meeting the EU's projected 2050 hydrogen demand of 41 Mt_{H2}/a at costs below 4.1 €/kg_{H2}, while simultaneously achieving CO_2 storage of 223 Mt_{CO2}/a. By coupling DAC and proton-exchange membrane (PEM) electrolysis, the freshwater demand for hydrogen production is significantly reduced by approximately 50%. The study highlights the economic feasibility of the system at CO_2 prices in a range of 200 €/t_{CO2}, emphasizing the critical role of carbon pricing in promoting hydrogen production and enabling large-scale CDR.**

***Index Terms*— carbon dioxide removal, direct air capture, electrolysis, hydrogen, techno-economic assessment**

I. INTRODUCTION

Hydrogen is widely regarded as a pivotal part of the energy transition, enabling the decarbonization of various sectors. Currently, hydrogen is primarily employed in the refining and industrial sectors, although future deployment in the transport and power generation sectors is anticipated [1],[2]. In the context of global efforts to achieve greenhouse gas (GHG) neutrality, the European Union (EU) has committed to reaching this target by 2050 under its Green Deal framework [3]. Meeting this ambitious goal is expected to generate substantial hydrogen demand, projected to reach approximately 41 Mt within the EU by 2050, as outlined in the Net Zero 2050 scenario [4]. The production of such volumes of hydrogen will require not only considerable renewable energy capacities but also significant quantities of water. Specifically, hydrogen production via electrolysis necessitates an estimated 17–23 liters of water per kilogram of hydrogen produced [5]. Given the anticipated increase in water stress globally [6], it is imperative to prioritize water-conscious hydrogen production methods to ensure sustainable development.

In addition to reducing emissions, large-scale carbon dioxide removal (CDR) is essential for achieving GHG neutrality [7]. For instance, under the Net Zero 2050 scenario, the EU is projected to achieve net negative CO_2 emissions of approximately 542 Mt by 2050 [4]. Alongside conventional CDR methods such as afforestation and reforestation, technological approaches such as direct air capture (DAC) and storage have attracted significant attention in recent years due to their scalability and long-term storage potential [8]. Among various DAC technologies, the most advanced employs a solid sorbent to adsorb CO_2 directly from the air [9]. This approach also captures water from the ambient air, which presents an opportunity for integration with downstream electrolysis processes, thereby reducing the freshwater demands associated with hydrogen production.

The integration of solid sorbent DAC and electrolysis has been explored by various researchers employing different methodologies and scopes. For instance, in [10], the combination of DAC and solid oxide electrolysis (SOEC) for synthesis gas production was examined, with a primary focus on developing operational strategies for the SOEC, while DAC was considered solely as a potential CO_2 supply. In [11] an energy management strategy for a combined DAC and electrolysis system powered by wind energy was proposed, where hydrogen produced from the electrolysis unit was combusted to supply the heat required by the DAC process. Similarly, in [12], the production of E-fuels through an integrated system comprising DAC, electrolysis, and Fischer-Tropsch synthesis powered by open-field photovoltaic (OFPV) systems was investigated. A notable conclusion from this study was that energy costs dominate the total E-fuel production costs, with the DAC unit contributing only about 7% to the overall cost. A combination of DAC, alkaline electrolysis and methanol synthesis powered by wind energy and installed inside the tower of a wind turbine was analyzed in [13]. While the research primarily focuses on the heat integration of the different components, the needed water for hydrogen production is completely supplied by the DAC plant and by water recovery from the methanol synthesis unit. In [14] a power-to-methane process utilizing CO_2 and water captured from ambient air via DAC and combined with a polymer electrolyte membrane (PEM) electrolyzer was investigated. The findings indicated a fourfold reduction in external water demand and demonstrated that high-temperature water recovery through condensation also facilitates significant heat integration. Finally, in [15] a DAC and PEM system for methane production was examined and it was found that the system can achieve water self-sufficiency [15].

While numerous studies have explored the integration of solid sorbent DAC and electrolysis, a significant gap remains in the form of comprehensive techno-economic assessments of such systems when coupled with renewable energy, particularly in high spatial and temporal resolution. To address this gap, the present study conducts a detailed techno-economic analysis, accounting for the impact of weather conditions on both the DAC unit and the energy system. The cost of the coupled system will be derived to assess the potential of providing hydrogen and CDR within the EU. Finally, the economic feasibility of the proposed system is analyzed by combining the cost with potential future CO_2 and hydrogen prices.

II. METHODOLOGY

A. Techno-economic Optimization

To assess the potential for water-conscious and CO_2-negative hydrogen production within the EU, a techno-economic single-node optimization model was developed and applied to each NUTS-1 region. The model operates with an hourly resolution and is implemented using the energy system optimization framework ETHOS.FINE [16]. Initially, the maximum technical potential in each region is derived by maximizing hydrogen production while accounting for the region's available energy generation (see Section D) and the energy demand of the process chain. Subsequently, to derive discrete cost curves, cost-optimization is performed for each region at production levels corresponding to 1, 2, 5, 10, 15, 20 and 25% of the maximum technical potential. The optimization minimizes total annual system costs while simultaneously optimizing the capacities of all units and their hourly operations throughout the year. This includes enforcing commodity balances and constraints such as the DAC's hourly resolved specific energy demand (see Section B). To ensure the availability of renewable energy for other applications, such as electrification, hydrogen production is limited to a maximum of 25% of its technical potential in each region.

The optimization model incorporates renewable energy generation via horizontal single-axis tracking (HSAT) OFPV systems and onshore wind turbines. Energy conversion technologies, including electric heaters and heat pumps, are utilized to supply low-temperature heat to the DAC plant. Energy storage options include battery storage and low-temperature heat storage. The process chain features PEM electrolysis, modeled with a fixed conversion efficiency of 70% (lower heating value, LHV), selected for its capability of dynamic operation [17], and solid sorbent DAC. Water storage is implemented using tanks, with no external freshwater supply included in the model. Consequently, water for electrolysis at each time step must be sourced from either the DAC plant or the water tank. The model also incorporates CO_2 transport and storage, assigned a fixed cost of 37 €/t_{CO2} based on [18], representing either pipeline or ship-based transport and storage. The primary techno-economic assumptions used in the analysis are detailed in TABLE 1.

The analysis targets the year 2050, aligning with the EU's GHG neutrality goals, while the weather year 2018 is employed as it represents an average year globally for renewable energy generation [19] and is consistent with the energy potentials utilized (see Section D). All monetary values are expressed in euros and adjusted for inflation to January 2024 using monthly inflation data from the European Central Bank [20]. A fixed discount rate of 6% is applied throughout the analysis.

TABLE 1. TECHNO-ECONOMIC ASSUMPTIONS.

Component	**Parameter**			
	CAPEX	***Fix OPEX [% of CAPEX]***	***Other***	***Based on***
HSAT OFPV	533 €/kW	3.0%	30 a lifetime	[21]–[23]
Onshore Wind	1552 €/kW	2.6%	30 a lifetime	[21],[22]
DAC	642 €/(t_{CO2}/a)	3.0%	25 a lifetime, variable OPEX 74 €/t_{CO2}	[24]
PEM	577 €/kW	2.0%	20 a lifetime, 70% efficiency LHV	[25],[26]
Battery	166 €/kWh	2.4%	15 a lifetime, charge-/discharge-/roundtrip-efficiency 96%/96%/85%	[22],[27]

B. Direct Air Capture Modeling

The employed DAC model is based on a one-dimensional process simulation developed using Aspen Adsorption [28]. This process model accounts for the simultaneous adsorption of CO_2 and water, incorporating the co-adsorption effects - i.e., the influence of water adsorption on CO_2 adsorption and vice versa. The commercially available adsorbent Lewatit® VP OC 1065 is used, chosen for its presumed similarity to the adsorbent utilized by Climeworks [29] and the availability of relevant data for parameterization [30]. The model employs a fixed-bed configuration with a heating jacket and a desorption temperature of 90 °C, enabling the integration of renewable energy into the desorption process. The DAC model has been optimized and simulated for various temperature and relative humidity conditions. Key performance indicators (KPIs), including thermal and electrical energy demands, productivity, and the water co-adsorption ratio, were determined from these simulations. Due to the complexity and nonlinearity of the detailed process model, its direct integration into the optimization framework for the techno-economic assessment was not feasible. Instead, a simplified linear model, based on the environmental conditions and the derived KPIs of the detailed process model, was utilized. Therefore, the hourly weather conditions were derived for each considered region from [31] and combined with the KPIs to derive the specific needed energy, productivity and water co-adsorption of the DAC plant for each hour of the year in each region.

The underlying process model represents an experimental plant operating under current technological conditions and is therefore not directly applicable for studies regarding the future. This limitation is particularly relevant as several studies project significant reductions in the energy demand of DAC systems due to advancements in process design and materials [32]. To incorporate these anticipated improvements, a correction factor was applied to the specific electricity and heat demands obtained from the process model. Based on the assumptions in [33], the energy demands were adjusted to reflect a 10% reduction in power demand and a 14.3% reduction in heat demand per decade, applied over a 25-year period. As future reductions in heat demand are expected to be enabled by decreased water adsorption through improved process designs or the development of new sorbents [34], the co-adsorption ratio was also reduced by the same factor as the heat demand. TABLE 2 presents the final specific average heat demand, electricity demand and the co-adsorption ratio for three exemplary regions within the EU, along with the average relative humidity and temperature. Additionally, the range of these values over the course of the year is indicated in parentheses.

TABLE 2. KPIS OF DAC PLANTS IN DIFFERENT REGIONS WITHIN THE EU.

KPIs	**Regions**		
	Southern Spain	***Southern Germany***	***Mainland Finland***
Temperature [°C]	16.4 (-0.3 – 37.4)	10.3 (-14.4 – 32.8)	3.5 (-22.4 – 30)
Relative Humidity [%]	66.3 (22.3 – 96.3)	74.6 (28.1 – 98.4)	80 (28.3 – 98.6)
Specific Power Demand [MWh/t_{CO2}]	0.5 (0.37 – 0.64)	0.5 (0.36 – 0.65)	0.5 (0.37 – 0.67)
Specific Heat Demand [MWh/t_{CO2}]	2.04 (1.45 – 2.83)	2.19 (1.48 – 2.92)	2.28 (1.47 - 3)
Co-adsorption Ratio [t_{H2O}/t_{CO2}]	1.5 (0.57 – 2.46)	1.63 (0.65 – 2.55)	1.63 (0.62 – 2.67)

Low relative humidity generally results in a lower specific heat demand and reduced water co-adsorption, as the sorbent adsorbs less water and requires less heat for desorption. Conversely, high temperatures increase the power demand because the working capacity of the sorbent decreases, leading to reduced CO_2 adsorption per cycle. Consequently, a greater airflow is required, which increases the power consumption of the fans and vacuum pump. As shown in Table 2, the average specific energy demand of DAC does not vary significantly across different regions. However, substantial temporal variations, as indicated by the ranges provided, are observed. These findings underscore the importance of employing a high temporal resolution in analyses, as done in this study.

C. Heat Pump Modeling

The coefficient of performance (COP) of the heat pump depends on the ambient temperature T_c and the target temperature T_h. The heat pump is modeled with a second law efficiency η of 50%, based on [35], and a target temperature of 100 °C, sufficient to supply the needed heat for the DAC plant, which operates at 90 °C:

$$COP = \frac{T_h}{T_h - T_c} * \eta \qquad (1)$$

For each region, the hourly temperature is obtained from [31], and the corresponding COP is calculated. This time series is used as an input for the techno-economic optimization model, defining a constraint that determines how much heat can be generated from one MWh of electricity in each hour by the heat pump.

D. Renewable Energy Generation

The utilized potentials and the hourly resolved generation profiles for HSAT OFPV and onshore wind turbines are based on analyses carried out in cooperation with the International Energy Agency for their Global Hydrogen Review 2024 [36]. For each NUTS-1 region, these potentials and generation profiles are incorporated into the model, serving to limit both the maximum installable capacity and the maximum operational output in each hour of the year.

III. RESULTS

A. Hydrogen Production Cost-potential

Figure 1 illustrates the cost potential of the combined hydrogen production and CDR system across the EU at the NUTS-1 level. In Figure 1a), the average cost of producing 25% of the maximum technical hydrogen potential in each region is presented as the levelized cost of hydrogen (LCOH). The results reveal that production costs are generally lower in the southern regions of the EU compared to central and northern Europe. The lowest production cost, approximately 3.1 €/kg_{H2} at 25% of the potential, is achieved in the Canary Islands. Despite the less favorable DAC conditions caused by the region's humid and hot climate, the excellent wind and solar resources lead to low energy costs, resulting in the lowest LCOH. Comparing central Germany and eastern Spain highlights the impact of renewable energy availability: although both regions exhibit similar DAC energy demands, central Germany faces significantly higher costs due to its poorer solar and wind conditions, resulting in the highest LCOH of 5 €/kg_{H2} in Thuringia.

The energy demand of the coupled system is primarily driven by the electrolysis unit, which requires approximately 47.6 kWh of electricity per kilogram of hydrogen produced. The DAC plant contributes a thermal energy demand ranging from 10.7 to 12.5 kWh/kg_{H2} and an electricity demand of 2.5 to 3 kWh/kg_{H2}, depending on the region. The total LCOH are significantly affected by the cost of the energy generation system, as shown in Figure 1b). A comparison of cost contributions between northern Spain (ES.1) and central Germany (DE.G) reveals that the notably higher LCOH in DE.G is largely attributable to the higher costs of the energy generation systems, including HSAT OFPV and wind turbines. For 25% of the technical potential, the energy generation system in ES.1 contributes approximately 1.5 €/kg_{H2} to the total LCOH, whereas in DE.G, energy generation accounts for around 3.2 €/kg_{H2}. The cost of the DAC unit remains relatively consistent across regions, contributing approximately 0.6 €/kg_{H2} to the LCOH. In contrast, the cost contribution of the PEM electrolyzer varies between regions and demand scenarios, reflecting the dependency of electrolyzer oversizing on local wind and solar conditions.

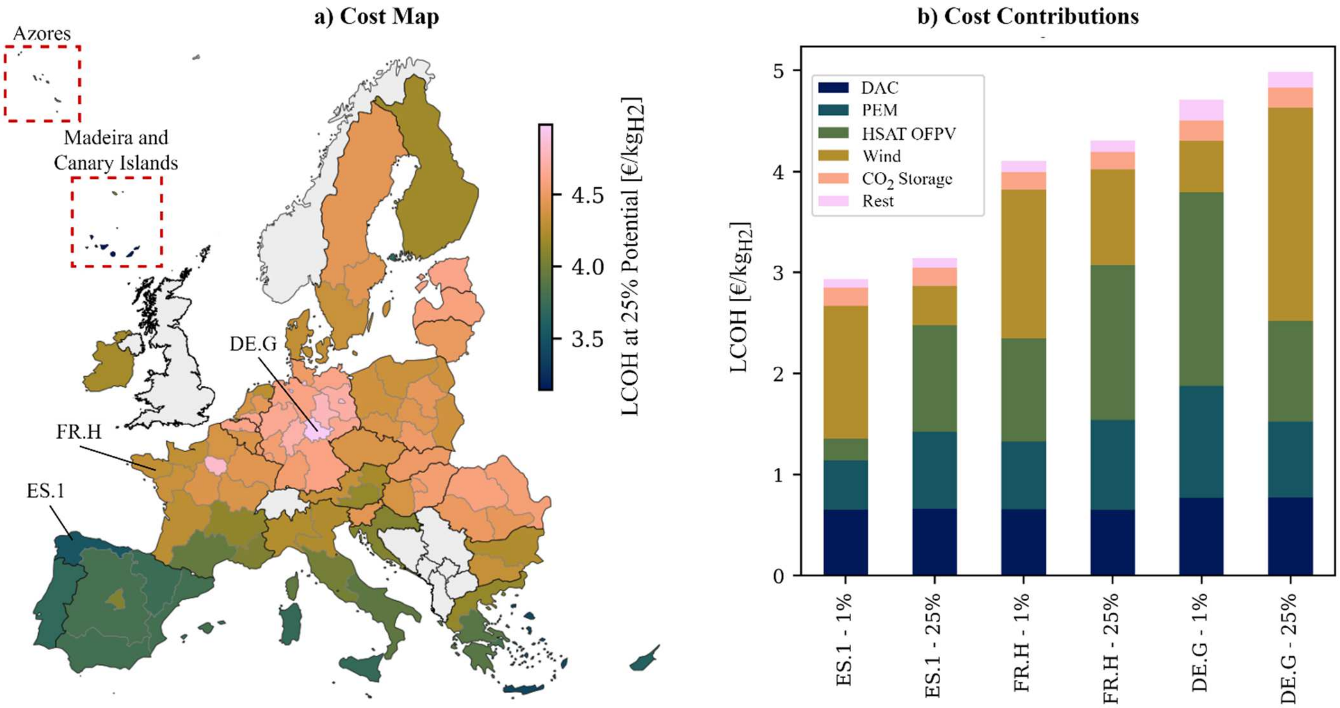

Figure 1. a) Average cost of hydrogen production for each NUTS-1 region in the EU by DAC and PEM electrolysis for 25% of the maximum technical potential. b) Cost contributions to the total LCOH for selected regions in Spain, France and Germany at 1 and 25% of the maximum technical potential.

Figure 2 presents the marginal cost of hydrogen production as a function of the cumulative production potential for selected regions. The results indicate a production potential exceeding 20 Mt/a on the Iberian Peninsula, with marginal costs of 3.8 €/kg$_{H2}$. Several regions demonstrate the capability to produce hydrogen at marginal costs below 4 €/kg$_{H2}$ including the Nordic region (Finland, Sweden and Denmark), Italy and France. Finally, the total projected hydrogen demand of approximately 41 Mt/a within the EU could be met at marginal costs of 4.1 €/kg$_{H2}$, with the Iberian Peninsula making a substantial contribution of approximately 21 Mt/a.

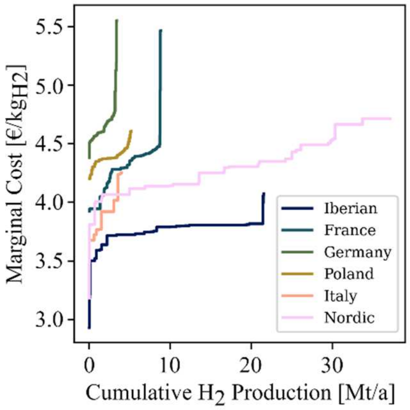

Figure 2. Merit order for selected regions and up to 25% of the technical potential.

B. *Negative CO_2-Emissions and Water Savings*

Meeting the EU's projected hydrogen demand by using the coupled DAC and PEM system would result in the annual CO_2 storage of approximately 223 Mt$_{CO2}$. This corresponds to an average of 5.44 kg$_{CO2}$ stored per kilogram of hydrogen produced. Generally, the quantity of stored CO_2 per produced hydrogen is affected by the location, as the co-adsorption ratio of the DAC plant depends on the prevailing weather conditions. In humid regions, the DAC plant tends to adsorb more water, resulting in lower CO_2 storage per produced hydrogen. For instance, the humid weather conditions in Ireland result in a specific CO_2 storage of approximately 4.55 kg$_{CO2}$/kg$_{H2}$, whereas the drier conditions in central Spain yield a specific CO_2 storage of about 6.05 kg$_{CO2}$/kg$_{H2}$. While the cost of CO_2 storage affects the LCOH, its impact is relatively minor, as shown in Figure 1b). For example, in Ireland, the assumed CO_2 storage cost of 37 €/t$_{CO2}$ contributes 0.17 €/kg$_{H2}$ to the total LCOH, whereas in central Spain, it contributes 0.22 €/kg$_{H2}$. Increasing the CO_2 storage cost to a more conservative 60 €/t$_{CO2}$ raises the LCOH contribution in central Spain to 0.36 €/kg$_{H2}$, while a reduction to 10 €/t$_{CO2}$ lowers it to 0.06 €/kg$_{H2}$. These findings highlight that, although the assumed CO_2 storage price has a noticeable influence, it is not a dominant factor in determining the overall LCOH.

The process chain demonstrates significant water-saving potential, as the DAC plant can supply the entire water feedstock required for PEM electrolysis. This results in a water saving of 9 liters per kg$_{H2}$, or, with respect to the total needed water, a reduction of approximately 50% can be achieved based on a total water demand of PEM electrolysis of 17.5 l/kg$_{H2}$ [5]. The water-saving potential is especially relevant given that the most cost-efficient hydrogen production within the EU is located in Spain, a country already suffering from water-scarcity and projected to experience an extreme level of water stress in 2050 [6].

C. *Economic Feasibility*

Figure 3 illustrates the hydrogen production potential of the proposed system within the EU as a function of possible hydrogen and CO_2 market prices. Therin, the CO_2 price represents revenues, e.g. from selling CO_2 certificates in carbon markets. For instance, at a hydrogen price of 2.25 €/kg_{H2} and a CO_2 price of 100 €/t_{CO2}, no hydrogen production is feasible within the EU, as indicated by the grey area. To enable the production of 41 Mt_{H2}/a (21 Mt_{H2}/a) for the often-cited target cost of CO_2 removal via DAC at 100 €/t_{CO2} would necessitate hydrogen prices of 3.35 €/kg_{H2} (3.2 €/kg_{H2}). At higher CO_2 prices, such as 220 or 250 €/t_{CO2}, hydrogen production volumes of 21 or 41 Mt/a could be achieved at hydrogen prices as low as 2.55 €/kg_{H2}.

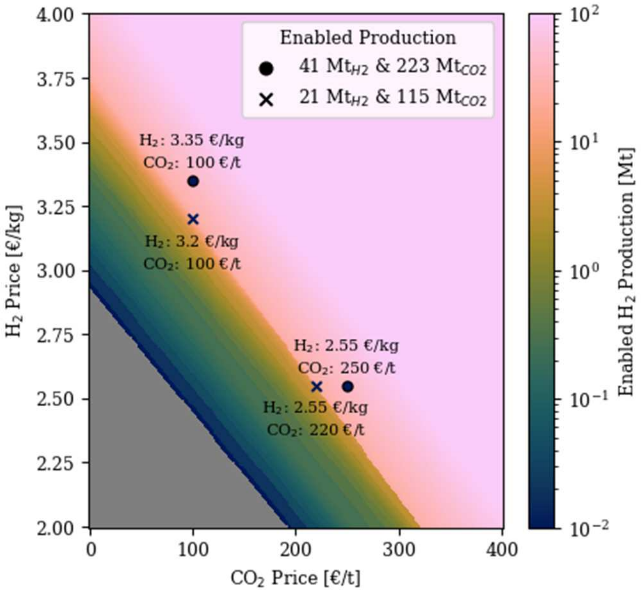

Figure 3. Influence of the H_2 and CO_2 market prices on the enabled H_2 production within the EU

The analysis of the two dotted points at the production level of 41 Mt_{H2}/a reveals that a 150 €/t_{CO2} increase in the CO_2 price leads to a 0.8 €/kg_{H2} reduction in the required hydrogen price. This relationship enables the derivation of the price correlation, calculated as the relative change in hydrogen price divided by the relative change in CO_2 price at constant supply (-0.8/3.35)/(150/100) = -0.16. The derived price correlation indicates that a change of the CO_2 price by +1% results in a change of the needed hydrogen price of -0.16%. Similarly, comparing the two markers at a CO_2 price of 100 €/t provides insights into the price elasticity of the hydrogen supply. Lowering the hydrogen price from 3.35 to 3.2 €/kg_{H2} reduces the supply from 41 to 21 Mt/a resulting in a price elasticity of the hydrogen supply of 10.9. This indicates that a -1% change in hydrogen price results in a -10.9% change in the supplied quantity. Finally, comparing the two markers at a hydrogen price of 2.55 €/kg_{H2} allows for deriving the cross-price elasticity of the hydrogen supply with respect to the CO_2 price. The resulting cross-price elasticity of 7 suggests that a +1% change in the CO_2 price results in +7% change in the enabled hydrogen supply. These metrics highlight the sensitivity of hydrogen supply by the proposed system to both hydrogen and CO_2 prices and underscore the interdependence of these factors in the economic viability of the coupled CDR and hydrogen production system.

The relatively high required hydrogen prices at a CO_2 price of 100 €/t_{CO2} underscore the economic challenges of hydrogen production using the proposed system within the EU under such conditions. However, more conservative projections of CO_2 prices exceeding 200 €/t_{CO2} present a more favorable economic scenario. At these higher CO_2 prices, the proposed system becomes competitive, as the additional revenue from CDR offsets the production costs.

IV. DICUSSION AND CONCLUSION

In this study, techno-economic optimization was utilized using the ETHOS.FINE framework to evaluate the potential of coupling hydrogen production and CDR within the EU. By incorporating the influence of weather conditions on both the renewable energy system and the DAC plant on a high spatial and temporal resolution, a comprehensive assessment under varying regional and temporal conditions is enabled.

The analysis of hydrogen production costs reveals a strong dependency on geographic location, with production costs ranging from approximately 3 €/kg_{H2} on the Iberian Peninsula, to around 5 €/kg_{H2} in central Germany. A detailed breakdown of costs reveals that the energy system required to power the process chain is the primary cost driver. The proposed system enables CDR at an average rate of 5.44 kg_{CO2} per produced kilogram H_2 while also achieving a significant reduction in freshwater demand for electrolysis by ~50%. This water-conscious approach to hydrogen production is particularly beneficial in regions with abundant renewable energy resources that are projected to experience water scarcity, such as Spain.

An economic analysis demonstrates the viability of the proposed system at a CO_2 price of 220 €/t_{CO2}, facilitating production of 21 Mt_{H2}/a in the EU at hydrogen prices as low as 2.55 €/kg_{H2}. The results highlight the importance of robust carbon pricing mechanisms to incentivize both hydrogen production and CDR technologies. By establishing CO_2 prices in the range of 200 €/t_{CO2} or higher, the proposed system could play a vital role in meeting the EU's hydrogen demand and greenhouse gas neutrality target while water resources are spared.

While this study concentrates on the EU, expanding the analysis to a global scale would be valuable, as varying weather conditions across regions influence both the operation of DAC systems and renewable energy generation. Additionally, this study primarily examines production costs, potentially neglecting spatial mismatches between hydrogen supply and demand. Incorporating transport costs into future research could provide a more comprehensive understanding of the system's economic viability and regional competitiveness.

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