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Green hydrogen production from offshore wind: A techno-economic analysis for Türkiye

Yasemin Balcı [a], Celal Erbay [b,*]

[a] Department of Energy and Technology Policies, Türkiye Energy, Nuclear and Mineral Research Agency, 06510, Ankara, Turkiye
[b] Department of Electrical and Electronics Engineering, National Intelligence Academy, 06100, Ankara, Turkiye

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ABSTRACT

This study investigates the economic viability of green hydrogen production using offshore wind energy in Türkiye, focusing on four regions: Ayvacık, Bozcaada, Edremit, and Bandırma. A techno-economic model was developed to estimate the levelized cost of hydrogen (LCOH) using 50 MW alkaline and polymer electrolyte membrane (PEM) electrolyzers. Results indicate that Ayvacık, with an LCOH of \$4.33/kg H_2 for alkaline electrolysis, is the most cost-effective location, while Bandırma, with the highest production costs, reaches an LCOH of \$5.85/kg H_2. Key cost drivers include capacity factor, capital expenditures (CAPEX), and government incentives such as local content support, which lowers Ayvacık's LCOH to \$4.13/kg H_2. These findings underscore offshore wind's potential to drive green hydrogen production in Türkiye, although regional factors significantly impact economic feasibility. This analysis highlights the strategic importance of optimal site selection, supportive policies, and technology advancements for expanding Türkiye's green hydrogen industry.

Nomenclature

BOP	Balance of plant	m	Meter
CAPEX	Capital expenditures	**m/s,**	Meters per second
CCS	Carbon capture and storage	**m^3**	Cubic meter
CCUS	Carbon capture, utilization and storage	**Mt**	Million tons
CO_2	Carbon dioxide	**Mtoe**	Million tonnes of oil equivalent
ED	Electrodialysis	**MW**	Megawatt
FİT	Feed-in tariff	**OPEX**	Operational expenditures
FO	Forward osmosis	**PEM**	Polymer electrolyte membrane
GW	Gigawatt	**R&D**	Research and development
Km	Kilometer	**RO**	Reverse osmosis
kW	Kilowatt	**SMR**	Methane reforming
kWh	Kilowatt-hour	**toe**	Tonnes of oil equivalent
LCOH	Levelized cost of hydrogen	**Wh**	Watt hour
LCOW	Levelized cost of pure water	**W/m^2**	Watt per square meter

1. Introduction

Green energy policy has gained significant popularity and attention from both scientific and technological sectors due to the rising global energy demand. Green energy, generally recognized as environmentally friendly and renewable, is crucial in addressing global warming, which is a major global challenge. Since the establishment of the United Nations Framework Convention on Climate Change in 1992, there has been a concerted international effort to evaluate climate change risks [1]. This extensive global initiative led to the signing of the Paris Agreement in 2015, which aims to enhance the global response to climate change threats. A worldwide shift in energy systems is urgently required to keep the average global temperature rise below 2 °C [2]. Therefore, improving energy efficiency and transitioning to a lower-carbon energy mix are essential.

The agreement outlined governments' commitments to reduce GHG emissions, as detailed in each country's nationally determined contributions [1]. The global economy's dependence on fossil fuels faces growing threats from both supply security and climate change. It is projected that oil and gas reserves will be exhausted by mid-century, with coal depleting about sixty years later. Concerns over the relentless use of fossil fuels and its link to accelerated climate change have driven political debates and policy development. Internationally, transitioning to renewable energy is seen as crucial for addressing these interconnected challenges. For instance, the European Union has set a

* Corresponding author.
E-mail address: c.erbay@mia.edu.tr (C. Erbay).

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new climate and energy framework aiming for at least a 27% share of renewable energy consumption by 2030 [3].

The various forms of renewable energy such as solar, wind, hydro, geothermal, and biomass play a pivotal role in shaping the global energy transition. These sources are not merely technical alternatives; they represent a major shift in how energy is produced and used, reflecting a deeper commitment to sustainability, resilience, and a more harmonious relationship with the environment. Historically, fossil fuels like coal, oil, and natural gas have been essential to the development and maintenance of global energy systems, supporting much of the modern world [4]. Countries' ambitions for renewable energy targets are driven by more than just a shift from traditional to sustainable energy sources. These targets form part of a broader, multi-dimensional strategy that integrates economic, geopolitical, environmental, and strategic factors. Economically, transitioning to renewable energy can create jobs, drive innovation, and decrease dependence on imported fuels, thus boosting energy security. Geopolitically, it can reshape a country's position in the global energy market by reducing reliance on unstable fossil fuel markets and potentially altering power dynamics. Environmentally, adopting renewable energy is crucial for tackling climate change and lowering greenhouse gas emissions. Strategically, setting high renewable energy goals can establish a country as a leader in the emerging green economy, shaping global trends and standards. In this way, renewable energy targets are a central component of a broader vision for a sustainable, resilient, and economically thriving future [5].

Decarbonization in the energy sector is receiving considerable focus due to its potential to reduce reliance on fossil fuels, mitigate environmental damage, and drive the search for alternative energy sources, all in pursuit of the Paris Agreement's target of achieving a climate-neutral society by 2050 [6]. Sectors such as transportation, electricity, heating, residential, agriculture, maritime, and manufacturing are all experiencing increasing energy demands over time. Currently, sectors like transportation, manufacturing and construction, and electricity and heat production are major contributors to GHG emissions from fuel combustion [7]. Hydrogen generated from green energy sources or low-carbon technologies holds significant promise for decarbonizing multiple sectors. It has the potential to mitigate climate impacts by cutting global greenhouse gas emissions and serves as a versatile energy carrier. Hydrogen is abundant and offers nearly three times the energy content per weight compared to gasoline, making it a compelling alternative to fossil fuels. Additionally, green hydrogen is a viable option for storing renewable energy. However, hydrogen's current role in the energy landscape is minimal, primarily due to the high production costs associated with generating hydrogen from renewable sources, which should ideally result in minimal to zero carbon emissions. Current hydrogen production methods largely rely on fossil fuels like coal and natural gas, which emit significant amounts of CO_2.

Blue hydrogen is generated via steam methane reforming SMR of natural gas, producing hydrogen and carbon dioxide. While the CO_2 is captured and stored underground, there is a potential risk of leakage, and the long-term implications of this storage are still uncertain. Gray hydrogen is produced through a similar process, but without capturing the CO_2, which is instead emitted into the atmosphere. Black hydrogen comes from coal gasification, where hydrogen is extracted from other gases using specialized membranes or absorbers, while the remaining gases are released into the air [8]. Green hydrogen, which is produced through water electrolysis. This process involves using an electric current to split water into hydrogen and oxygen, with no greenhouse gas emissions, provided the electricity comes from renewable sources. Water electrolysis requires the use of an electrolyzer, with different techniques available depending on the electrolyte type. These techniques include alkaline electrolysis, PEM electrolysis, solid oxide electrolysis [9]. Alkaline and PEM electrolysis are the most established and commonly used in commercial hydrogen production, typically operating at temperatures ranging from several tens of degrees Celsius. Alkaline and PEM electrolyzers are particularly well-suited for use with renewable energy sources due to several key benefits. They can efficiently handle variable loads, making them adept at managing the fluctuations in renewable energy generation, such as from wind and solar power [10]. This adaptability allows PEM electrolyzers to optimize the use of renewable energy resources more effectively. Given these advantages and the potential of green hydrogen to reduce GHG emissions, this research focuses on evaluating both the environmental and economic aspects of producing green hydrogen using offshore wind power systems. Comparison of economic feasibility, carbon footprint, and sustainability information of H_2 production by different methods are given in Table 1.

Hydrogen generated from offshore wind holds significant promise for delivering substantial amounts of clean energy during the global transition to sustainable energy. The feasibility of using offshore wind for hydrogen production hinges on various factors, including local and geographical conditions. Offshore wind provides more consistent and reliable energy compared to onshore wind and solar power, which translates to higher and more stable production levels. This stability ensures that electrolyzers operating on offshore wind can achieve higher load factors, making them more efficient. Consequently, the reliable and robust energy output from offshore wind can greatly enhance the advancement of green hydrogen initiatives [14].

Transitioning from fossil fuels to renewable energy sources is essential for reducing future emissions and mitigating their impacts. However, the growth of renewable energy, particularly the variable production of wind energy, presents economic challenges to the current energy system. As the wind energy market expands, land constraints are increasingly directing investors towards offshore wind projects, as establishing onshore wind farms becomes more difficult. A significant challenge in developing offshore wind farms is selecting the optimal location, which is a complex and time-consuming process that requires evaluating various criteria across technical, environmental, and socio-economic factors, while also adhering to relevant regulations [15]. Technically, wind capacity is the most critical factor. Environmental considerations are also crucial and routinely assessed, as wind farms can have significant impacts on ecosystems, such as harming wildlife (including birds and bats), causing turbine noise, and affecting visual landscapes. Environmental factors encompass CO_2 emissions, nitrogen oxide emissions, and water usage. Empirical findings indicate that an increase in economic factors is significantly linked to a rise in installed wind energy capacity. Economic factors primarily relate to the acquisition, management, and development of land for wind farms [16]. Social and political factors, such as local acceptance of offshore wind farms, potential negative effects on fish stocks, reductions in property values, and adverse consequences for tourism, play a crucial role in planning. Integrating these social factors into quantitative planning

Table 1
Comparison of H_2 production methods (data from Refs. [11–13]).

Primary energy source	Method	LCOH ($/kg$H_2$)	Carbon footprint (CO_2/kg)	Sustainability
Wind energy	Electrolysis	3.5–12	0.4–0.8	Sustainable as long as energy source is available
Solar energy	Electrolysis	4–11	1.7–4.4	Sustainable as long as energy source is available
Nuclear energy	Electrolysis	3.5–7	0.1–0.3	Consistent energy supply
Natural gas	SMR (with CCUS)	2–3	1.5–6.2	High water consumption
Natural gas	SMR (without CCUS)	1–2.5	10–13	High emissions and water use
Coal	Gasification (without CCUS)	1.8–3	22–26	Significant greenhouse gas contributions

models is essential for accelerating the deployment of onshore wind turbines by identifying feasible potential early in the planning stage [17].

In several countries, the development of offshore wind energy is closely linked to the growing demand for green H_2 and the industrial opportunities it presents [18]. For some nations, establishing a strong industrial case for offshore wind is crucial, integrating it into broader renewable energy strategies. This approach not only supports the adoption of green H_2 but also fosters synergies with the production of essential wind industry components, such as green steel, thus reducing the sector's carbon footprint. Germany is making substantial strides in this area through its national hydrogen strategy, which includes significant investments in infrastructure for hydrogen transport, storage, and distribution. One of the project is a notable example, aiming to develop 10 GW of offshore wind-powered green hydrogen capacity in the North Sea [19]. In The Netherlands, one of the project will establish a 10 GW offshore wind farm in the North Sea to produce up Mt of green H_2 annually by 2040, serving industrial clusters in the Netherlands and Germany [20]. The UK's national hydrogen strategy includes projects like the Kintore Hydrogen development in Scotland, which aims to use excess offshore wind electricity to produce green H_2 for carbon-intensive industries [21].

Hydrogen demand is set to rise significantly as it supports decarbonization, with offshore wind providing a viable energy source for electrolyzers. By 2050, the LCOH in European seas is projected to decrease from ~6.5 $/kg (2020) to ~2.43 $/kg, making green hydrogen increasingly competitive with gray hydrogen; offshore electrolysis is expected to shift closer to shore, making it viable even for shallower waters [22]. Another study analyzes the economics of hydrogen production from offshore wind in the UK, revealing that the LCOH is between $9.37/kg and $11.33/kg based on different types of electrolyzers [23]. Based on the research conducted by the World Bank, the offshore wind potential is projected to be 75 GW in Türkiye [24]. The regions with the higher offshore potential identified are the Marmara and Aegean seas (the regions selected for this study). The offshore wind hydrogen production potential for Türkiye is estimated to be 15.17 million tons [25]. The recent study proposed a model for green hydrogen production using a 9.9 MW offshore wind farm in Samandağ, Türkiye. The cost of producing hydrogen in this facility is estimated at $5.6/kg, highlighting its potential for cost reductions with future technological advancements [26]. Prior studies have identified high CAPEX for offshore infrastructure, technological challenges associated with electrolysis efficiency, and logistical hurdles in integrating offshore wind energy with hydrogen production systems. Recent techno-economic analyses have examined these challenges in regions with established offshore wind industries, such as Northern Europe, but there is limited research specifically addressing the techno-economic viability of green hydrogen from offshore wind in regions like Türkiye. This gap is especially relevant as Türkiye has substantial wind potential along its coasts, yet little is known about the specific costs, and regional variances for green hydrogen production in this context.

This study aims to fill this gap by conducting a techno-economic assessment of green hydrogen production from offshore wind in Türkiye, with a focus on four key regions: Ayvacık, Bozcaada, Edremit, and Bandırma. These locations are chosen due to their varied wind capacities and unique regional characteristics, providing insights into the cost-effectiveness of green hydrogen across Türkiye's coastline. By calculating the LCOH for different electrolyzer technologies, this research highlights critical factors influencing economic feasibility, including capacity factors, CAPEX, and the potential impact of policy incentives. It develops a tailored techno-economic model for 50 MW electrolyzers, enabling a nuanced analysis of cost drivers. Based on the calculations, Ayvacık is identified as the most cost-efficient location with a hydrogen production cost of $4.33/kg H_2 for alkaline electrolysis, further reduced to $4.13/kg H_2 with local content support. By integrating site-specific analysis with policy-driven cost optimization, the research bridges critical knowledge gaps and provides a scalable framework for advancing green hydrogen production in Türkiye, while highlighting the strategic importance of offshore wind as a reliable renewable energy source. To our knowledge, this is one of the first studies to analyze green hydrogen production from offshore wind specific to Türkiye's context, offering valuable insights into its regional viability and the strategic importance of supportive policies to foster growth in Türkiye's hydrogen economy. These contributions establish a foundational reference for advancing offshore wind-powered green hydrogen initiatives in Türkiye and similar emerging markets.

2. Offshore wind potential in Türkiye

Türkiye's energy transition, which started in the 2000s, significantly accelerated after 2015. Despite its limited fossil fuel resources, Türkiye has substantial potential in renewable energy. Consequently, Turkish energy policy focuses heavily on diversifying and ensuring the sustainability of its energy sources. In 2020, Türkiye's primary energy consumption was 147.2 Mtoe. By 2035, this is projected to increase to 205.3 Mtoe. The average annual increase in primary energy consumption was 3.1% between 2000 and 2020, while it is expected to be 2.2% from 2020 to 2035. Per capita primary energy consumption, which was 1.7 toe per person in 2020, is expected to rise to 2.1 toe per person. The share of renewable energy sources in primary energy consumption, which was 16.7% in 2020, is projected to increase to 18,4% 23.7% by 2025 and 2035, respectively. Nuclear energy is expected to reach a 5.9% share by 2035. The share of fossil fuels, which was 83.3% in 2020, is projected to decrease to 70.4% by 2035. The share of coal will drop to 21.4%, while oil and natural gas will decline to 26.5% and 22.5%, respectively [27].

The projected installed capacities of hydro, wind, and solar power in GW for the years 2025, 2030, and 2035 as shown in Fig. 1. Hydropower capacity is expected to increase slightly from 33 GW in 2025 to a stable 35.1 GW by 2030 and 2035, indicating a steady contribution to the energy mix. Wind power is projected to grow more significantly, with capacity rising from 13.1 GW in 2025 to 18.1 GW by 2030, and then reaching 29.6 GW by 2035. This reflects a rapid expansion in wind energy, driven by technological advancements and increased investments. Solar power is anticipated to see the most dramatic growth, with capacity surging from 17.9 GW in 2025 to 32.9 GW by 2030, and further increasing to 52.9 GW by 2035. This substantial increase in solar capacity highlights a major shift towards solar energy, supported by falling costs and technological improvements. Overall, the data indicates a significant transition towards renewable energy sources, with solar power leading the way in growth [27].

Türkiye has a total of 48 GW of wind energy potential, with 8 GW classified as highly efficient and 40 GW as moderately efficient in terms of economically useable potential. Wind power was first incorporated into Türkiye's energy mix in 1998, and by the end of 2014, the country had installed a capacity of 3.6 GW, with an average annual increase of 500 MW, particularly since 2007. By 2019, the installed wind power capacity had reached 7.6 GW [28]. As of 2020, Türkiye's installed onshore wind energy capacity stood at 8.8 GW, with no offshore wind capacity recorded. The capacity for onshore wind energy is projected to grow significantly in the coming years, reaching 13.1 GW by 2025 and further increasing to 18.1 GW by 2030. By 2035, it is expected to reach 24.6 GW, reflecting a robust and sustained growth in onshore wind installations. In contrast, offshore wind energy capacity is currently zero and is expected to remain unchanged until 2035, when it is projected to reach 5 GW (Fig. 2). This indicates a future expansion into offshore wind power, complementing the growth in onshore wind energy and contributing to Türkiye's overall renewable energy strategy. This projected increase in wind energy capacity, particularly in onshore wind, highlights Türkiye's commitment to enhancing its renewable energy infrastructure. The anticipated growth aligns with global trends toward increasing reliance on renewable energy sources to meet climate goals and reduce carbon emissions [27].

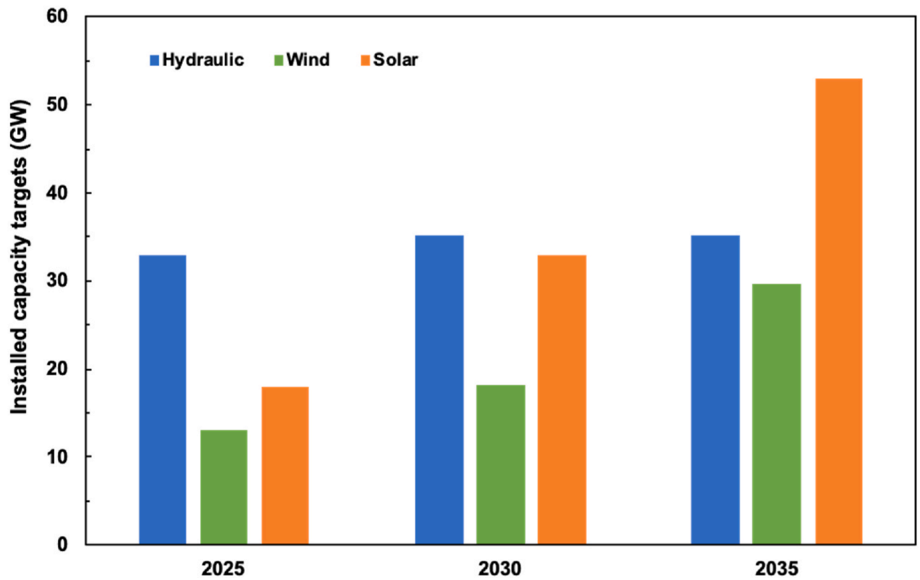

Fig. 1. Installed renewable energy capacity targets in 2025, 2030, and 2035 by source in Türkiye (data from Ref. [27]).

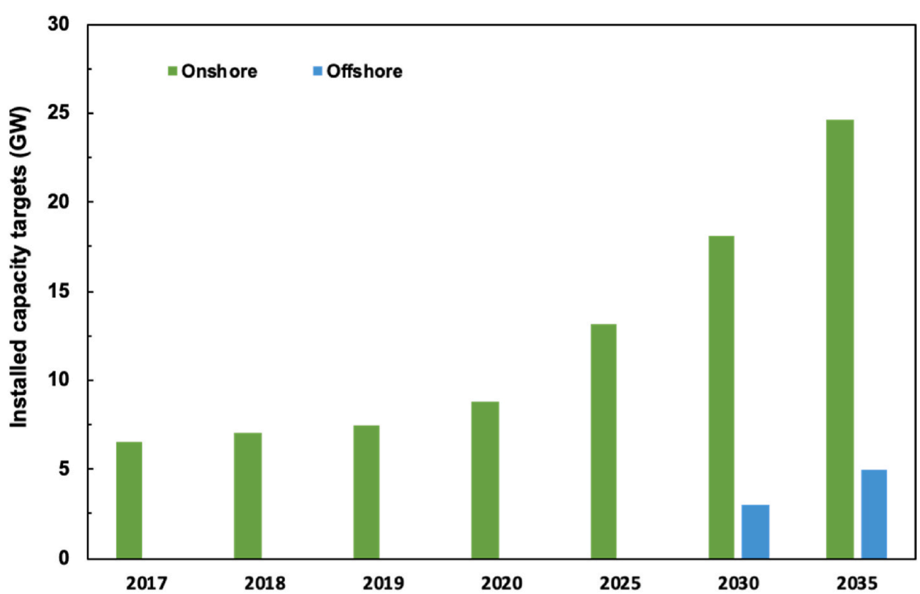

Fig. 2. Variation in installed wind energy capacity in Türkiye over the years (data from Ref. [27]).

Türkiye, strategically situated as a bridge between Europe and Asia, spans 783,562 km^2 and is bordered by the Black Sea, Mediterranean Sea, and Aegean Sea, totaling 8333 km of coastline when excluding islands. The Black Sea's coastline measures 1700 km, the Aegean Sea's 2805 km (excluding islands), and the Mediterranean's 1577 km. Given Türkiye's proximity to neighboring continental shelves and its critical coastal safety considerations, a thorough and specific analysis is essential for estimating the country's offshore wind energy potential [29]. Despite being surrounded by seas on three sides, it was surprising to find that most wind energy research focuses on land rather than offshore. A review of the literature revealed that there are only a few localized studies on offshore wind energy. Türkiye's prime wind energy potential is along the Marmara and Aegean coasts and at higher elevations, where average annual wind speeds reach 6.9 m/s at 50 m. The eastern Mediterranean coasts, from northern to southern areas, also show significant potential [29]. Other promising regions include the southern part of Türkiye, the western Black Sea coast, and southeastern Anatolia, with average annual wind speeds of 6.4 m/s and above at 50 m [30]. Site selection is crucial for offshore wind farm projects, impacting both technical and economic aspects. Identifying potential site limitations can offer investors significant time and cost benefits. Researchers must consider various regional factors, such as harbor access, navigation routes, marine archaeological sites, protected waterscapes and landscapes, underwater pipelines, military zones, and oil and gas drilling areas [31].

The potential of the offshore wind energy capacity at various locations along Türkiye's four coastal seas (Marmara, Black Sea, Aegean Sean and Mediterranean) was calculated [32]. Considering regional factors, the offshore wind energy potential has been estimated as follows: 1293 MW for Mersin, 780 MW for Karasu (Black Sea), 600 MW for Bandırma (Marmara), 564 MW for Bozcaada (Aegean Sea) and 528 MW for Gökçeada (Aegean Sea). Offshore wind potential was analyzed in 55 Turkish regions using meteorological data and multi-criteria methods, recommending Bozcaada, Bandırma, Gökçeada, İnebolu, and Samandağ as the best sites, with an estimated total capacity of around 1629 MW [33]. It is estimated that about 3295 km^2 of Türkiye's maritime area, or approximately 1.4% of the total sea area, is suitable for offshore wind

Table 2
The wind energy potential across different regions of Türkiye. Adapted from Refs. [37,38].

Region	Annual Average Wind Speed (m/s)	Annual Average Wind Density (W/m^2)
Marmara	3.29	51.91
Aegean	2.65	23.47
Mediterranean	2.45	21.36
Middle Anatolia	2.46	20.14
Black sea	2.38	21.31
Eastern Anatolia	2.12	13.19
South-eastern Anatolia	2.69	29.33
Average	2.58	25.82

farms [34].

The theoretical wind energy potential in Türkiye is vast, estimated to be roughly twice the country's current electricity consumption. Türkiye's technical wind energy potential is about 88,000 MW, while its economic potential is around 10,000 MW. Reports from the State Electrical Studies Board suggest that Türkiye's wind energy potential could be approximately 120 billion kWh. Studies indicate that Türkiye's total wind energy potential exceeds its current thermal and hydroelectric energy production [35,36]. Table 2 displays the annual average wind speeds and wind energy densities across various regions in Türkiye. It shows that wind power densities are notably higher in the Marmara, Aegean, and South-East Anatolian regions, which also have the highest wind speeds. Annual average wind speeds vary from 2.12 m/s in Eastern Anatolia to 3.29 m/s in Marmara. According to the General Directorate of State Meteorological Studies, Türkiye's overall annual mean wind speed is 2.58 m/s, and the wind power density is 25.82 W/m^2. The Marmara, South-East Anatolian, and Aegean regions are identified as the most promising for wind energy, with wind speeds exceeding 3 m/s in many areas [37,38].

3. Methodology

The primary methodological contribution of this study is the creation of a techno-economic model to calculate the LCOH. The custom techno-economic model is employed to evaluate two distinct scenarios, which include: (1) onshore alkaline electrolysis and (2) onshore PEM electrolysis. Fig. 3 presents the model's underlying infrastructure.

Green H_2 production from offshore wind energy mainly can be achieved in two distinct ways. One approach involves having the electrolyzer, desalination plant, compressor, etc. located on the offshore platform [39]. In this model, the produced $H_2$is transported to shore via a pipeline with the aid of the compressor, where it can then be utilized or stored. This setup enables the integration of renewable energy production with H_2 transport infrastructure, optimizing the use of offshore resources and potentially reducing the need for onshore facilities [40]. In this model the offshore wind farm represents the largest portion of both system CAPEX and OPEX, whereas electrolysis incurs lower costs. Among the components, the wind farm and the offshore platform are the primary contributors to CAPEX, while OPEX is most significantly impacted by the wind farm and salt-cavern storage. Costs associated with compression, desalination, and pipelines are minimal, constituting less than 1% of both CAPEX and OPEX [40]. The second model involves situating the desalination plant, compressor, storage, electrolyzer, etc. onshore, while the offshore wind energy is transmitted to shore via a transmission line. In this configuration, the H_2 is produced onshore using the electricity supplied from the offshore wind farm. The H_2 is then either used directly or stored for future use. This approach separates the H_2 production and storage facilities from the offshore platform, potentially simplifying the offshore infrastructure and allowing for more controlled and centralized management of the production process on shore [41]. The second model, which involves situating the desalination plant, compressor, storage, and electrolyzer onshore while transmitting offshore wind energy to the shore via a transmission line, has been selected for this study. The decision to select the second model, which situates the desalination plant, compressor, storage, and electrolyzer onshore, presents several advantages. One key benefit is the potential for reduced capital and operational expenditures, as onshore facilities can often be constructed and maintained more economically than their offshore counterparts. This configuration also simplifies the offshore infrastructure, allowing for a more streamlined setup that minimizes logistical challenges. Moreover, with H_2 production occurring onshore, there is enhanced flexibility in managing resources, optimizing operations, and integrating additional renewable energy sources.

LCOH elements of techno-economic model of this study for H_2 production from offshore wind energy is detailed in Fig. 4. The calculation of LCOH includes three main elements, namely; CAPEX, OPEX and electricity cost. CAPEX includes three major elements: (1) the offshore wind farm, (2) the electrolyzer system, and (3) Desalination. Also, OPEX includes (1) maintenance and (2) operational costs. For the offshore wind farm CAPEX; development and project management encompass all tasks leading up to financial closure or the formal authorization to start offshore wind farm construction. This includes obtaining planning permissions, such as conducting an environmental impact assessment, as well as defining the design and engineering details. The cost for a 10 MW wind turbine is approximately $13.1 million [40]. This cost covers both the components and the installation, including assembly, supplier-related aspects, and warranty. The installation and commissioning costs, which generally surpass approximately $1.3 million per

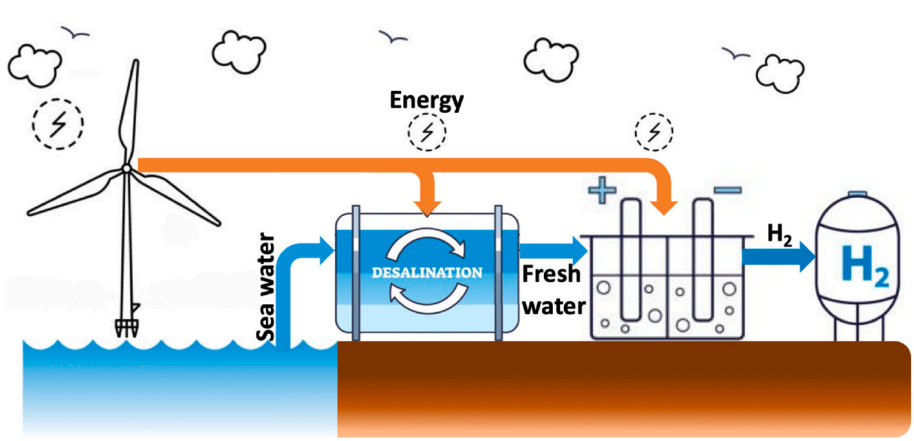

Fig. 3. Schematic diagram of the techno-economic model setup to produce green H_2 from offshore wind plant by using sea water. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

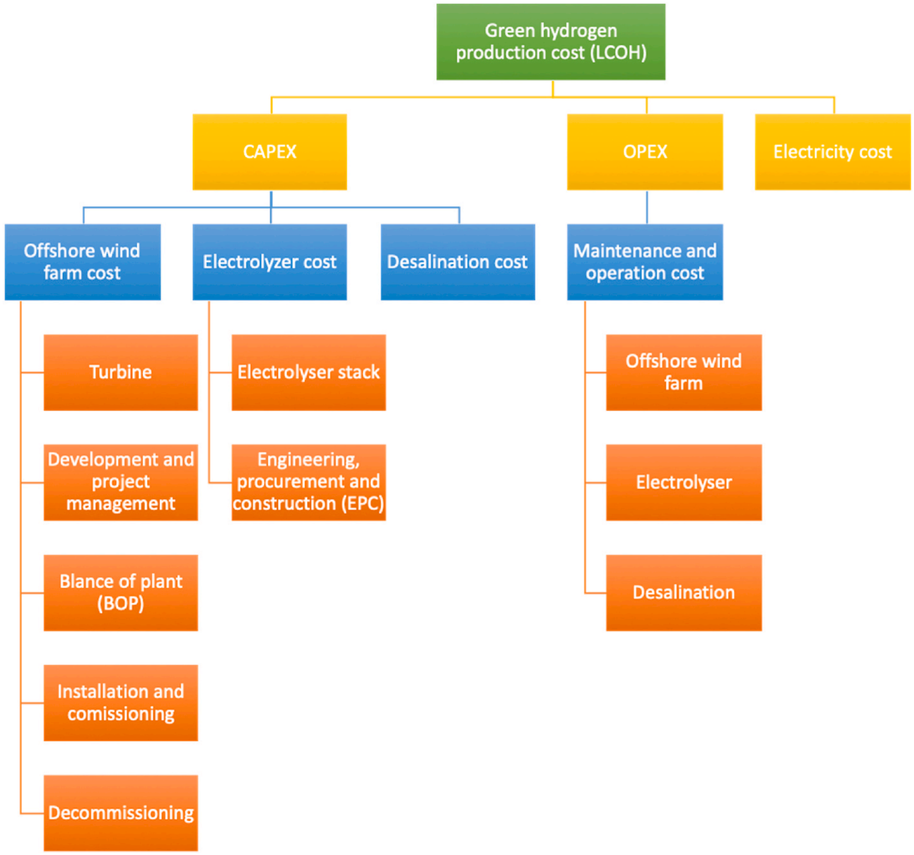

Fig. 4. Organizational chart detailing the LCOH elements of the techno-economic model for this study, including a breakdown of both CAPEX and OPEX.

MW scale turbine [40,42], are primarily associated with logistics, staff expenses at the head office, the construction port, the installation vessel, and the turbine itself. These costs involve mechanical and electrical work, testing, pre-handover inspections, and troubleshooting. The BOP encompasses all elements of the wind farm other than the turbines, including the transmission infrastructure specifically constructed for the wind farm. This includes, cables, turbine foundations, offshore substation, onshore substation, operations base. The installation and commissioning of the BOP and turbines involve both land-based and sea-based operations. For offshore activities, the process begins with transporting components from the nearest manufacturing port to either the construction port or directly to the site. This process concludes when the wind farm construction is finished and the assets are transferred to the operational teams. Decommissioning cost involve dismantling or deactivating offshore infrastructure at the end of its operational life, along with disposing of the equipment. Offshore wind farm OPEX involve overseeing the asset's management, including health and safety, control and functioning of both the wind turbines and BOP, remote site monitoring, environmental oversight, electricity sales, administrative duties, marine operations supervision, vessel operation, quayside infrastructure management, and back-office functions.

In this study, it is assumed that a 50 MW alkaline and PEM electrolyzers are used. Specific energy consumption taken as 49,44 kWh/kgH_2 and 50,56 kWh/kgH_2 for alkaline and PEM, respectively [43]. To provide sufficient electricity for 50 MW alkaline and PEM electrolyzers capacity and desalination plant, required total offshore wind power capacity was calculated based on the capacity factors for different regions. Table 3 outlines key assumptions and design conditions for the modeling of green hydrogen production using offshore wind energy. It specifies the types of electrolyzers, their energy consumption rates, plant lifetime, and desalination parameters.

Available power of a wind turbine can be calculating by Equation (1), which is determined as follows.

$$\text{Power (W)} = \frac{1}{2} \text{ x } \rho \text{ x Cp x A x } (Wspd)^3 \tag{1}$$

where, ρ, C_p, A and W_{spd} denotes the air density, coefficient of performance, swept area of wind turbine blades and wind speed, respectively.

The required electrolyzer capacity can be calculated by using Equation (2) and the capacity factor (*CF*) can be estimated with Equation (3).

$$Electrolyser\ capaciy\ (kW) = \frac{Max\ imum\ possible\ daily\ electricity\ generation\ (kW)}{24x\ \beta\ x(EC(electrolyser) + EC(BOP) + EC(Desalination))} \tag{2}$$

$$CF = \frac{\sum Daily\ Electricity\ Generation\ (kW)}{CE(kW)\ \ x\ 24x\ 365x\ PL\ (year)} \tag{3}$$

where, *EC* is electricity consumption for electrolyzer, *BOP* systems and desalination. β is the hourly hydrogen production capacity of Alkaline and PEM electrolyzers. *CE* is the electrolyzer capacity and *PL* is the lifetime of wind plant.

The required installed power from the offshore wind plants based on different regions have been calculated with Equation (4) while required annual energy for 50 MW alkaline and PEM electrolyzes are calculated by using Equations (5) and (6), respectively. The amount of electricity expected to be produced by offshore wind plants with different installed capacities, modeled for the Ayvacık, Bozcaada, Bandırma, and Edremit as shown in Fig. 5, has been calculated by using Equation (7) [44]. Also, the remaining energy after accounting for the electricity used by the desalination plant is given in Table 4. The CAPEX value of offshore wind farm is given as approximately $2705 per kW include turbine cost, BOP, development and project management, installation, and decommissioning [45–47]. The OPEX value is taken as 1.9% of the CAPEX value [48]. Based on this, the total CAPEX and OPEX values for the required offshore wind installed capacities are shown in Table 4.

$$Installed\ power\ (kW) = \frac{Electrolyser\ capacity\ (kW)}{Capacity\ Factor} \tag{4}$$

$$\text{Required energy (kWh)} = \text{Hydrogen production(kg) x } \left(49.44\,\frac{\text{kWh}}{\text{kg}}\right) \tag{5}$$

$$\text{Required energy (kWh)} = \text{Hydrogen production(kg) x } \left(50.56\,\frac{\text{kWh}}{\text{kg}}\right) \tag{6}$$

$$\text{Annual Energy Production} = \text{Capacity factor x } \left(\text{RatedPower (kW)x } 8760\,\frac{\text{h}}{\text{year}}\right) \tag{7}$$

Table 3
List of all assumptions and design conditions for modeling.

Variables	Numbers/Details
Electrolyzer capacity (MW)	50
Energy consumption for alkaline and PEM (Kwh/kg H_2)	49.44/50.56
Capacity factor for Ayvacık, Bozcaada, Edremit, and Bandırma (%)	50.5/50.2/44.3/34.6
Plant lifetime (years)	27
Required energy for desalination (Kwh/m^3 H_2O)	5
Water consumptions for desalination (m^3/kg)	0.009
Water cost for desalination ($/kg H_2)	1.1
Weighted average cost of capital (%)	5
Electricity cost	FİT and calculated LCOE
Onshore facilities	Desalination plant and electrolyzer
Wind power capacity requirement	Calculated based on regional capacity factors

The offshore wind farms at Ayvacık, Bozcaada, Bandırma, and Edremit exhibit distinct cost profiles based on their capacities. Ayvacık and Bozcaada each have a capacity of 100 MW and incur identical total costs for both CAPEX and OPEX. Specifically, both locations require a total CAPEX of $2705 and an OPEX of $51.4, reflecting their equal scale and investment requirements. This uniformity suggests that these locations are comparably efficient for projects with a capacity of 100 MW. In contrast, Bandırma, with the largest capacity of 145 MW, incurs the highest total costs. The total CAPEX for Bandırma is $392.2 million, and the OPEX amounts to $7.5 million. The elevated CAPEX and OPEX align with its larger scale, indicating that Bandırma is suited for larger projects where the higher initial and ongoing investments are justifiable. Edremit, with a capacity of 110 MW, presents a middle ground between Ayvacık/Bozcaada and Bandırma. Its total CAPEX is $270 million, and the OPEX totals $5.1 million. These numbers are higher than those for Ayvacık and Bozcaada but lower than those for Bandırma, reflecting its intermediate capacity and cost structure. Overall, the CAPEX per MW is consistent across all locations at $2,705, making the total CAPEX a direct function of the capacity. Similarly, the OPEX per MW remains constant

Fig. 5. Offshore wind farm locations used in this study of Northwest in Türkiye (Marmara region view from Google Earth).

Table 4
Cost of techno-economic model approximate calculation based on different regions.

Parameters	Ayvacık	Bozcaada	Edremit	Bandırma
Capacity factor (%)	50.5	50.2	44.3	34.6
Required installed power (kW)	100,000	100,000	115,000	145,000
Annual energy production (MWh)	442,400	439,800	446,300	439,500
Remaining energy after desalination (MWh)	393,100	390,800	396,600	390,500
Required annual energy for 50 MW alkaline electrolyzer (MWh)	309,000	309,000	309,000	309,000
Required annual energy for 50 MW PEM electrolyzer (MWh)	316,000	316,000	316,000	316,000
CAPEX (million $)				
Offshore wind farm total CAPEX	270.5	270.5	297.6	392.2
Development and project management	15.2	15.2	16.7	22.1
Turbine	127.0	127.0	139.7	184.2
BOP	7.6	7.6	8.4	11.0
Installation and commissioning	82.6	82.6	90.8	119.7
Decommissioning	38.1	38.1	41.9	55.2
50 MW PEM electrolyzer total CAPEX	78.665	81,377	74,852	68,808
50 MW alkaline electrolyzer total CAPEX	54.474	55.581	52.273	48,791
Desalination plant total CAPEX	0.06	0.06	0.06	0.06
Total OPEX (million $)				
Offshore wind farm	5.1	5.1	5.7	7.5
50 MW PEM electrolyzer	1.573	1.627	1.497	1.376
50 MW alkaline electrolyzer	1.089	1.111	1.045	0.975
Desalination plant	0.0012	0.0012	0.0012	0.0012

at $51.4, resulting in higher total OPEX for larger capacities. Consequently, Ayvacık and Bozcaada offer cost efficiency for smaller projects, Bandırma is ideal for large-scale operations despite its high costs, and Edremit provides a balanced option with moderate costs and capacity. The choice of location depends on specific project needs, budget constraints, and desired capacity, making it essential to consider these factors when planning offshore wind projects.

Saline water desalination is a common method for producing freshwater from saltwater by reducing its salinity to levels suitable for drinking, irrigation, and other uses. Salinity levels vary by source, with groundwater being less saline and seawater more saline. Various desalination technologies include RO, FO, and ED. The RO process involves applying high pressure to push water through a porous membrane, effectively removing salt without changing the water's phase [49]. The RO system for desalination consumes 2–5 kWh/m^3 of electrical energy and has a recovery ratio of 30–50%, without using thermal energy. The FO system, a newer membrane technology, can recover up to 90% of the water and operates with minimal external hydraulic pressure, consuming 2–4 kWh/m^3 of electrical energy [50]. However, FO faces challenges such as internal concentration polarization and lower efficiency. ED is another established desalination method that uses alternating anion and cation-selective membranes to separate ions under an electrical field, allowing ions to move towards their respective electrodes. This method is used for various applications, including recovering water and chemicals from wastewater and desalinating brine. ED is effective for high-salinity feeds due to its high recovery rate and low fouling tendency, but its energy consumption increases with higher salinity levels. Globally, ED desalination constitutes around 4% of the total desalination capacity [51]. The treatment costs for saline and brackish water using various desalination technologies are reported as follows: (a) ED costs $0.6/m^3 for large-scale operations and between $0.6 and $1.05/m^3 for smaller-scale operations. (b) RO costs range from

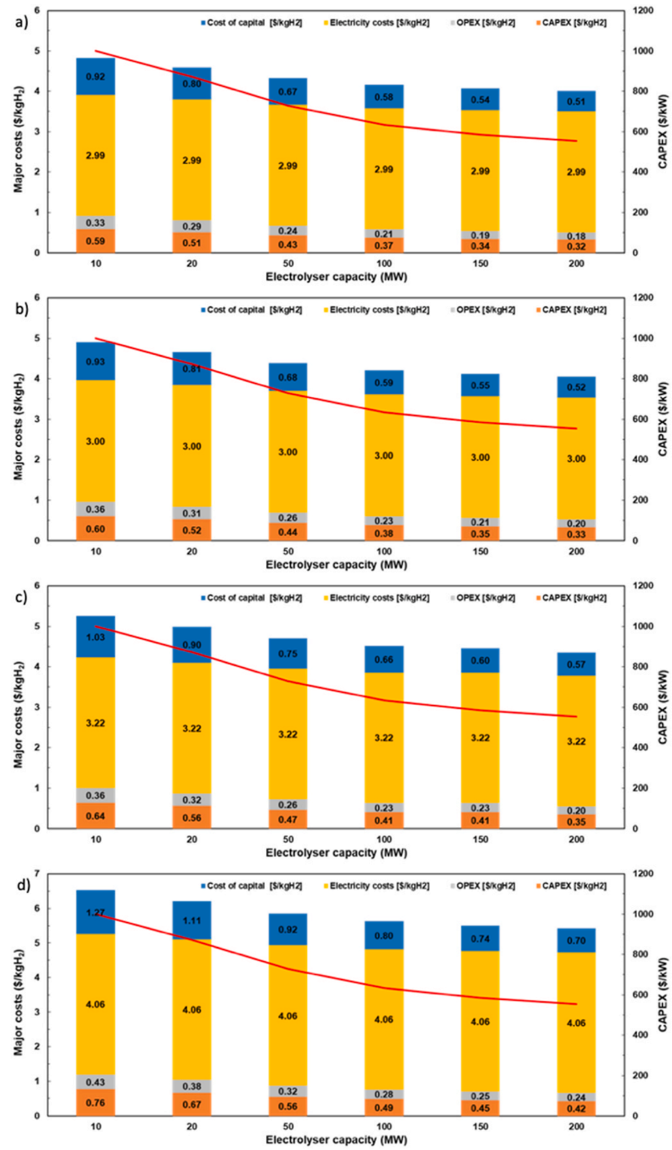

Fig. 6. Share of the major cost drivers in LCOH for different electrolyzer capacities (stack graph) and predicted electrolyzer CAPEX as a function of module size for alkaline technology (red line) for a) Ayvacık, b) Bozcaada, c) Edremit, d) Bandırma. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

$0.26 to $0.54/m^3 for large-scale applications and from $0.78 to $1.33/m^3 for medium-sized operations [52]. Desalination OPEX is 2%, as the desalination CAPEX already encompasses the total cost of water. Desalination is necessary due to the technical requirements of the electrolyzers, and both compression and desalination processes demand additional electricity. Desalination requires 5 kWh/m^3 H_2O [53]. Since producing 1 kg of H_2 necessitates 0.009 m^3 of H_2O. The LCOW is calculated based on Equation (8) [54].

$$LCOW\left(\frac{\$}{ton}\right)=\frac{\frac{TCC}{n}+TOC}{mpw}x\ \frac{i(1+i)^n}{(1+i)^n-1} \tag{8}$$

where TCC is the total capital cost; TOC is the total operating cost; m_{PW} is the mass of pure water by each plant during a year; n is the operating year of the plant; i is the interest rate.

Over the past twenty years, advancements in seawater desalination have significantly lowered water production costs, leading to greater global adoption, especially in arid regions. Despite these improvements, high desalination costs still prevent many countries from using these technologies as a fresh water source. To address this, there is a need to enhance R&D aimed at further reducing desalinated water costs [55]. The goal is to make affordable, readily available fresh water through seawater desalination. Key areas for continued R&D include [56]: To enhance the efficiency and cost-effectiveness of seawater desalination, several key areas warrant focused research and development. Economic and technical evaluations of various desalination processes are crucial to identifying the most viable options. Concurrently, there is a need for the development of efficient power and water cogeneration systems to optimize resource use. Utilizing nuclear and solar energy can further support sustainable desalination practices. Additionally, advancing chemical treatment methods for seawater and improving thermal distillation processes at higher temperatures are essential for enhancing desalination efficiency. Investigating hybrid systems can also provide benefits by combining the strengths of different technologies. Integrating and optimizing the use of electricity, steam, and water resources will maximize overall efficiency. Moreover, selecting and developing cost-effective construction materials, improving RO membranes, and addressing scale and corrosion management will contribute to reducing operational costs. Finally, advancements in large-scale desalination plants will be key to meeting the growing global demand for freshwater.

4. Results and discussion

The cost of green H_2 is influenced by several factors including the price of electrolyzers, the location of production, the method used, facility capacity, and the lifetime of the equipment. While scaling up production can reduce costs, substantial progress is required to cut electrolysis expenses, such as discovering optimal materials and establishing extensive supply chains. Supportive government policies and financial incentives are crucial for advancing renewable energy sources like solar and wind, which can lower green electricity prices. The lack of CO_2 emissions provides a strong incentive for industry investment. However, significant reductions in green H_2costs are not expected until the 2030s [57]. The final cost of H_2 is largely influenced by the expense of producing green H_2 from renewable sources, which includes CAPEX for electrolyzer plants and the cost of renewable electricity. The location of production is crucial, as it impacts the efficiency of renewable energy use. CAPEX forecasts are uncertain due to variables like financing costs and electrolyzer efficiency, requiring reasonable assumptions. On the supply side, production costs for technologies such as alkaline electrolysis are expected to decrease over time due to economies of scale. On the demand side, large-scale projects, including H_2refueling stations, benefit from cost savings and competitive advantages. Understanding these factors is vital for a thorough analysis of H_2 project costs [58].

4.1. LCOE and LCOH

Electrolyzer system CAPEX can be summarized as a function of module size using various sources from literature and calculated based on the following Equation (9) [59]:

$$\text{CAPEX scaling factor} = X^{-0.1976} \tag{9}$$

Where X represents the electrical rated power of the electrolyzer system, ranging from 10 MW to 200 MW. Using this scaling factor, CAPEX or

Table 5
Calculated LCOE values from offshore wind farms produced in different regions using alkaline and PEM electrolyzers.

Regions	Alkaline ($/MWh)	PEM ($/MWh)
Ayvacık	57.72	60.71
Bozcaada	57.92	61.18
Edremit	62.11	64.72
Bandırma	78.25	80.04

LCOH calculations can be made for electrolyzers with varying capacities. The model used in this study consists of 50 MW alkaline and 50 MW PEM electrolyzers. By using Equation (9) and the CAPEX values of alkaline ($1000/kW [60]) and PEM ($1300/kW [46]) electrolyzers, the CAPEX values have been calculated for different electrolyzer capacity. In comparing the electrolyzer plant costs across the four regions—Ayvacık, Bandırma, Bozcaada, and Edremit—several trends are shown in Fig. 6. Full load hours (hours/y) are taken as 4,423, 4,404, 3885 and 3033 for Ayvacık, Bozcaada, Edremit and Bandırma, respectively [61]. Ayvacık generally offers lower CAPEX and cost of capital compared to Bozcaada, making it a more cost-effective choice for H_2production. For instance, Ayvacık's CAPEX ranges from $0.59 to $0.32/kgH$_2$, whereas Bozcaada's is higher, ranging from $0.33 to $0.6/kgH$_2$. Similarly, the cost of capital in Ayvacık ranges from $0.51 to $0.92/kgH$_2$, while Bozcaada's figures are higher, peaking at $0.93/kgH$_2$. This disparity contributes to Bozcaada having the highest total LCOH, reaching $5.71/kgH$_2$ for smaller capacities. On the other hand, Edremit shows a competitive edge with lower CAPEX and cost of capital compared to both Bozcaada and Ayvacık, particularly for larger plants. Edremit's CAPEX ranges from $0.35 to $0.64/kgH$_2$, and it's cost of capital ranges from $0.57 to $1.03/kgH$_2$. Bandırma strikes a balance, with LCOH values ranging from $5.18 to $6.28/kgH$_2$.

LCOE is calculated by using Equation (10) with using costs from Table 4 [40]. This metric represents the actual cost of producing electricity in terms of H_2 output, providing a comprehensive view of the economic viability of H_2 production in different regions. Calculated LCOE for alkaline and PEM electrolyzer are given in Table 5.

$$\textit{Calculated LCOE}\ (\$\,/\,MWh) = \frac{\sum_{t}^{n} (CAPEX + OPEX)p}{\sum_{t}^{n} \textit{Required Energy for Hydrogen Production}\ (MWh)} \tag{10}$$

where p represents plant include offshore wind farm, desalination plant and electrolyzer. t denotes the year, and all terms are summed over the years from construction to the system lifetime, n. The calculations have been made excluding the weighted average cost of capital.

LCOH values are calculated according to Equation (11). Specific energy consumption for alkaline and PEM are 177,987 kJ/kg and 182,036 kJ/kg, respectively [62]. Lifetime of both electrolyzer system is 30 years. Lifetime stack for alkaline electrolyzer consider as 8000 h [47] while 6000h for PEM [46].

$$\text{LCOH} = \frac{LHV}{\eta_{sys}, LHV}\left(\left(\frac{\frac{i}{100}\cdot\left(1+\frac{i}{100}\right)^{n}}{\left(1+\frac{i}{100}\right)^{n}-1} + \frac{OPEX}{100}\right)\frac{CAPEX}{\tau} + E\right) \tag{11}$$

LCOH is a crucial metric in evaluating the economic viability of H_2 production systems. It represents the cost per kg of H_2 produced over the lifetime of the project, factoring in capital and operational expenses, as well as the discount rate. The formula for calculating LCOH involves several components. Firstly, the CAPEX represents the initial investment

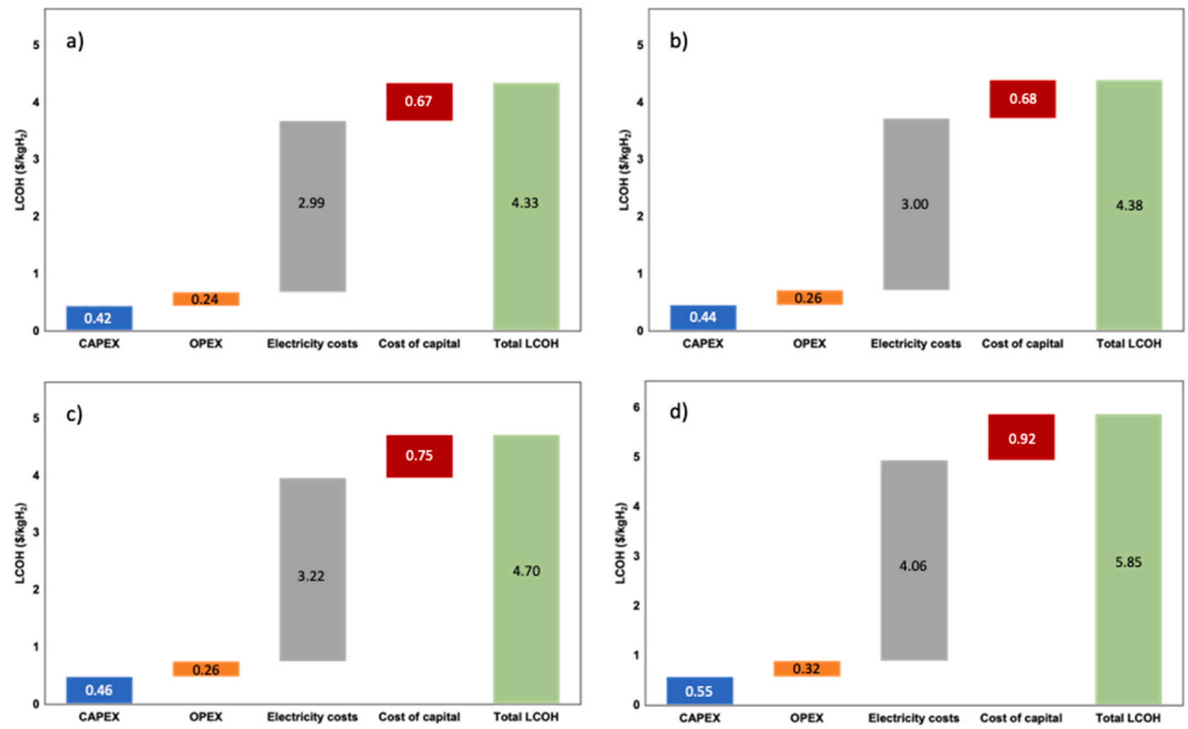

Fig. 7. Major cost drivers LCOH for 2024 for a) Ayvacık, b) Bozcaada, c) Edremit, d) Bandırma for 50 MW alkaline electrolyzer system.

required for setting up the hydrogen production system, typically expressed in $/kW. OPEX account for the ongoing costs associated with operating and maintaining the system, usually as a percentage of the capital expenditures per annum (% CAPEX/a). The system efficiency (ηsys, LHV) is a critical factor determining how effectively electricity is converted into H_2, considering the lower heating value of H_2 (LHV) in Wh/kgH_2. Full load hours (τ) represent the number of hours the system operates at maximum capacity annually, influencing the utilization of the system. Electricity costs (E) play a significant role since H_2 production often involves electrolysis, where electricity is used to split water into H_2 and oxygen. These costs are measured in $/kWh. Discount rate (i) is another crucial parameter reflecting the time value of money and risk associated with the investment. It is typically expressed as a percentage. The lifetime (n) represents the lifetime of the electrolyzer system.

Based on the calculations, Bandırma has the highest total LCOH at $5.85/kg$H_2$ as shown in Fig. 7. The primary driver of this cost is the electricity expense, which stands at $4.06/kg$H_2$, making it the most substantial component. This high electricity cost suggests that Bandırma may face challenges in energy sourcing or higher tariffs, which adversely impacts overall production costs. The CAPEX of $0.56/kg$H_2$ is also notable, indicating a considerable initial investment requirement that could further strain project viability. Edremit demonstrates a lower total LCOH of $4.70/kg$H_2$, representing a significant reduction compared to

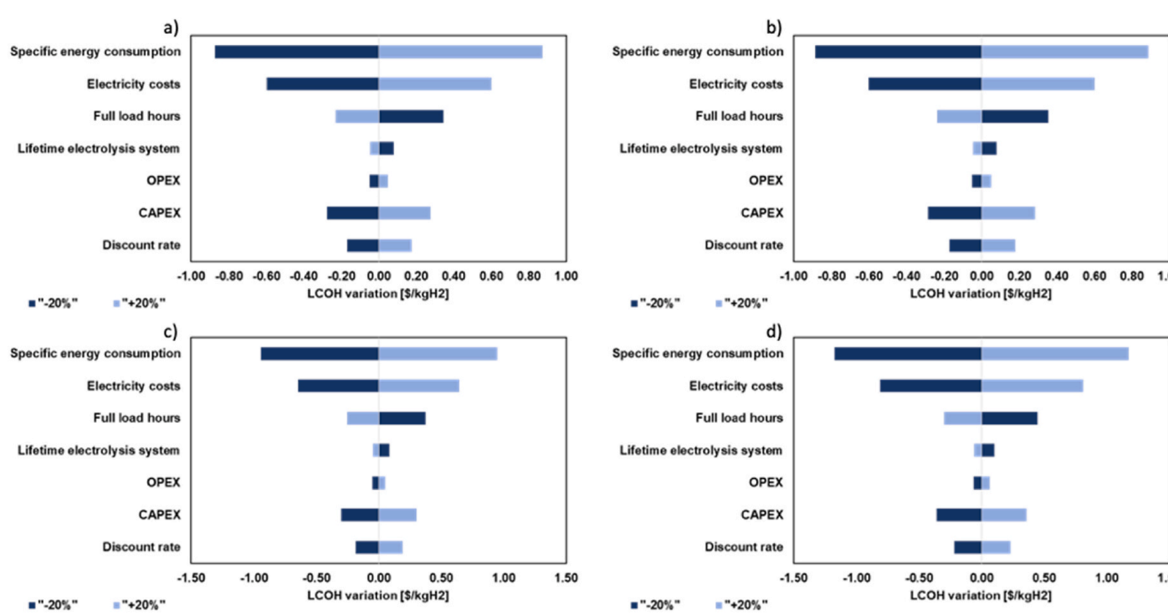

Fig. 8. Sensitivities of the cost share in 2024 for a) Ayvacık, b) Bozcaada, c) Edremit, d) Bandırma for 50 MW alkaline electrolyzer system.

Bandırma. This decrease is largely due to more favorable electricity costs, which are at \$3.22/kgH_2. The lower electricity prices may reflect better energy sourcing options or lower operational costs. Additionally, Edremit's CAPEX of \$0.47/kgH_2 indicates a more manageable initial investment, potentially making this region more attractive for H_2 production projects. Ayvacık offers the most competitive total LCOH at \$4.33/kgH_2, a further reduction compared to both Bandırma and Edremit. The region benefits from the lowest electricity costs at \$2.99/kgH_2, showcasing efficient energy sourcing or favorable pricing conditions. The CAPEX here is also the lowest at \$0.43/kgH_2, which suggests that Ayvacık provides the most cost-effective environment for hydrogen production. This combination of low operational and capital costs positions Ayvacık as a potentially leading region for future H_2 initiatives. Bozcaada, with a total LCOH of \$4.38/kgH_2, sits between Ayvacık and Edremit. Its electricity costs are at \$3.00/kgH_2, which, while higher than Ayvacık, is still competitive. The CAPEX of \$0.44/kgH_2 aligns closely with the other regions, making it a viable option for H_2 production. Although it doesn't lead in cost efficiency, Bozcaada offers a balanced approach to production expenses. Overall, Ayvacık stands out as the most economically favorable region for H_2 production, with both the lowest total LCOH and CAPEX (Fig. 7).

4.2. Sensitivity analyses

A tornado plot showing the result of the sensitivity analysis for electrolyzer systems across Ayvacık, Bandırma, Bozcaada, and Edremit highlights notable differences in how various parameters affect each location as shown in Fig. 8. The tornado plot ranks the variables that have a statistically significant relationship to the conditional mean. Those at the top with the largest bars exert the key cost driver. The bars represent the possible values of the conditional mean calculated for a change in the variable with the values showing the cost at ±20 %. Specific energy consumption causes the most significant changes to LCOH calculation, which is the key cost driver. Ayvacık shows the highest sensitivity to changes in discount rates, with values of −0.17 and + 0.17, and CAPEX values of −0.28 and + 0.28 at ±20 %. This indicates that fluctuations in these areas have a more significant impact on Ayvacık compared to other locations. Additionally, Ayvacık's OPEX experiences a notable reduction of 0.05 at −20%, and its system is highly sensitive to variations in electricity costs, with a positive impact of 0.60 at +20%. In comparison, Bandırma, Bozcaada, and Edremit exhibit higher sensitivities. Bandırma's CAPEX impact is ±0.36, OPEX impact is ±0.06, and electricity cost impact is ±0.81, showing higher pronounced effects than Ayvacık at ±20 % sensitivity. Bozcaada's CAPEX impact is ±0.28 and OPEX is ±0.05, with electricity costs at ± 0.60, reflecting moderate sensitivity. Edremit's CAPEX impact is ±0.30 and OPEX is ±0.05, with electricity costs at ±0.64 for ±20% sensitivity. indicating a similar effect on energy efficiency. Furthermore, Bandırma is the most affected by changes in the lifetime of specific energy consumption (±1.17), underscoring its vulnerability to these factors. Overall, Bandırma is particularly sensitive to financial and operational factors, while other regions like Ayvacık, Bozcaada, and Edremit may benefit from focusing on optimizing energy efficiency and managing operational costs more effectively. The sensitivity analysis highlights that Bandırma is generally more sensitive to changes in CAPEX, OPEX, discount rates, and electricity costs compared to the other regions. Ayvacık, Bozcaada, and Edremit show lower sensitivities in these areas, but exhibit less impact on specific energy consumption proportional to full load hours. It is observed that regions with lower full load hours have less impact of specific energy consumption on LCOH calculations.

4.3. Comparison of LCOE and LCOH values for hydrogen production

The comparison of LCOE values for H_2 production reveals significant regional variations. Table 6 presents the LCOH values for four different regions according to three different LCOE tariffs: FiT (\$73.64/MWh [63]), FiT with local content support (\$55.99/MWh [63]), and Calculated LCOE. The FiT represents the price received per kg of H_2 produced, influenced by government incentives or subsidies. This tariff provides a financial baseline for the value of H_2 production. The FiT with local content support is an adjusted rate that incorporates additional government incentives aimed at reducing the cost of electricity from offshore wind farms when produced with local content. This support helps lower the overall cost of H_2 production by promoting local investment and infrastructure. In contrast, the calculated LCOE reflects the LCOE derived from the offshore wind farms, desalination plant, and electrolyzers.

For Ayvacık, the FiT LCOE is \$5.15 per kg for alkaline electrolyzers and \$5.75 for PEM electrolyzers, which decreases to \$4.13 and \$4.73 respectively with li. The Calculated LCOE for Ayvacık is the lowest among the regions, at \$4.33 per kg for alkaline and \$5.09 for PEM electrolyzers, highlighting its cost-effectiveness. In Bozcaada, the FiT LCOE is slightly higher at \$5.19 for alkaline and \$5.16 for PEM electrolyzers, with local content support reducing these costs to \$4.28 and \$4.78 respectively. The calculated LCOE increases to \$4.38 for alkaline and \$5.16 for PEM electrolyzers, reflecting a slight rise compared to Ayvacık. Edremit shows a further increase in costs with a FiT LCOE of \$5.30 for alkaline and \$5.97 for PEM electrolyzers, which drop to \$4.67 and \$4.93 respectively with local content support. The calculated LCOE is \$4.70 for alkaline and \$5.50 for PEM electrolyzers, indicating higher production costs relative to Ayvacık and Bozcaada. Bandırma has the highest LCOE values among the regions, with a FiT LCOE of \$5.61 for alkaline and \$6.44 for PEM electrolyzers, reduced to \$4.73 and \$5.40 respectively with local content support. The calculated LCOE is \$5.85 for alkaline and \$6.78 for PEM electrolyzers, reflecting the highest overall production costs. In summary, Ayvacık is the most cost-effective region for H_2 production, followed by Bozcaada, Edremit, and Bandırma, which has the highest costs. The data demonstrates that local content support can significantly reduce FiT costs, but the overall calculated LCOE still varies considerably based on regional factors. This emphasizes the necessity of robust policy frameworks to stimulate investment in green hydrogen infrastructure. Without such incentives, the economic feasibility of large-scale green H_2 production may remain constrained, particularly in regions with higher CAPEX and operational expenditures.

Overall, the results underscore the critical role that regional factors, such as capacity factor and CAPEX, play in determining the LCOH. Ayvacık emerges as the most cost-effective location, with a LCOH of \$4.33/kgH_2 for alkaline electrolysis, largely due to its higher capacity

Table 6
LCOH for 50 MW alkaline and PEM electrolyzers across four regions based on different LCOE values.

Parameters	Ayvacık		Bozcaada		Edremit		Bandırma	
	Alkaline	PEM	Alkaline	PEM	Alkaline	PEM	Alkaline	PEM
FiT (\$/MWh)	73.64							
LCOH (\$/kgH_2)	5.15	5.75	5.19	5.83	5.30	5.97	5.61	6.44
FiT with local content support (\$/MWh)	55.99							
LCOH (\$/kgH_2)	4.13	4.73	4.28	4.78	4.67	4.93	4.73	5.40
Calculated LCOE (\$/MWh)	57.72	60.71	57.92	61.18	62.11	64.72	78.25	80.04
Calculated LCOH (\$/kgH_2)	4.33	5.09	4.38	5.16	4.70	5.50	5.85	6.78

factor and relatively lower CAPEX. In contrast, Bandırma, despite having the highest installed capacity, exhibits the highest LCOH ($5.85/$kgH_2$), primarily attributed to its lower capacity factor and increased capital costs. These findings suggest that optimal site selection for offshore wind farms is crucial for minimizing production costs, and merely increasing installed capacity does not guarantee cost advantages. This study also compares the performance of alkaline and PEM electrolyzers. Alkaline electrolyzers consistently demonstrate lower LCOH across all regions due to their lower specific energy consumption and CAPEX, making them more suitable for cost-sensitive applications. However, PEM electrolyzers, despite having higher LCOH, offer certain operational advantages, including higher efficiency at variable loads and better compatibility with intermittent renewable energy sources. This suggests that the choice of electrolyzer technology should be application-specific, with alkaline electrolysis preferred for large-scale, steady-state production, and PEM electrolysis more suitable for scenarios where renewable energy input may fluctuate.

Green H_2 presents several advantages and challenges as a clean fuel. On the positive side, it offers substantial environmental benefits by producing no harmful emissions, which improves air quality and supports overall environmental health. It can be produced using renewable energy sources such as solar and wind, making it a sustainable choice for various energy needs. Additionally, green H_2 is highly efficient in energy conversion, particularly when used in fuel cells to generate electricity, and it can be easily stored and transported through existing natural gas infrastructure, making it suitable for diverse applications in industries and vehicles [64]. However, green H_2 also faces several disadvantages. Its production is currently expensive, involving high costs associated with renewable energy and the process of splitting water to obtain H_2. The adoption of green H_2 requires significant infrastructure development for its storage and transportation, necessitating substantial investment and ongoing efforts. Safety concerns also arise, as H_2 can be dangerous if mishandled or if leaks occur, requiring stringent safety protocols. Furthermore, the technology needed for the efficient storage, transport, and use of green H_2 is still in development, and advancing these technologies to a commercially viable level involves considerable time and resources [64].

Despite the strong investment appeal due to the absence of CO_2 emissions, significant reductions in green H_2 costs are not expected until the 2030s [57]. Currently, the most affordable H_2 production methods are conventional ones like gray and black H_2, which depend on fossil fuels. Their costs fluctuate based on the type of fossil fuel used and are influenced by factors such as CO_2 taxes or energy shortages. Black H_2 (produced from coal without CCS) is the cheapest, costing between \$1.8/kgH_2 and \$3/kgH_2, followed by gray H_2, which ranges from \$1/kgH_2 to \$2.5/kgH_2. As CO_2 taxes increase, these prices are expected to rise, making green H_2 more competitive after 2030. By then, gray and black H_2 prices are anticipated to be about \$2-\$4/kgH_2 and \$2-\$5 per kg, respectively. Meanwhile, the cost of green H_2 produced from solar is expected to drop from nearly \$4 to \$11/kgH_2 to around \$1.5/kgH_2 to \$5/kgH_2 by 2030 (Table 7) [12]. Also, the hydrogen production cost is around \$6.1/kgH_2 by using 8 MW solar-powered high-temperature electrolysis system [65]. Another study indicates that the cost for green hydrogen through solar thermal technology is between \$5.10 and \$10/kgH_2 [66]. Among nations working to integrate H_2 as an energy source, Türkiye stands out due to its high renewable potential and ambitious "Türkiye Hydrogen Technologies Strategy and Roadmap". The country boasts a combined wind and solar capacity exceeding 50 GW by 2030 and operates at exceptionally high-capacity factors. By 2030, Türkiye is projected to have H_2 production costs globally estimated at \$2.4/kgH_2 [67]

Table 7
Hydrogen production costs based on different energy sources and methods (data from: [12]).

Primary energy source	Method	Hydrogen color	LCOH (\$/kgH_2)
Solar energy	Electrolysis	Green	4–11
Wind energy	Electrolysis	Green	3.5–12
Offshore wind energy	Electrolysis	Green	4–12
Offshore wind energy	Electrolysis	Green	4.13–6.44 (**this study**)
Nuclear energy	Electrolysis	Pink	3.5–7
Natural gas	SMR (with CCS)	Blue	2–3
Natural gas	SMR (without CCS)	Gray	1–2.5
Coal	Gasification (without CCS)	Black	1.8–3

Technological challenges also play a substantial role in determining the feasibility of offshore wind-to- H_2 projects. The integration of desalination processes to provide the requisite water for electrolysis adds to both the CAPEX and operational complexities of such systems. The use of reverse osmosis desalination, with its energy demands, must be carefully considered in the overall cost structure of H_2 production. Additionally, the offshore wind sector faces inherent logistical and technical hurdles, including turbine installation, maintenance, and transmission infrastructure, which further impact the economic viability of these projects. Moreover, the study underscores the necessity of advancing infrastructure for H_2 transport and storage. While offshore wind provides a stable energy source for hydrogen production, scaling these systems will require extensive development of storage and distribution networks. Collaborations between government entities, private sector investors, and international stakeholders will be crucial to address these infrastructure needs and ensure the successful integration of H_2 into Türkiye's energy mix. Green H_2 production from offshore wind presents a viable pathway for Türkiye's energy transition. However, realizing its full potential will depend on optimizing regional site selection, improving electrolyzer technology, addressing technical challenges, and maintaining strong policy support. As Türkiye seeks to diversify its energy portfolio and reduce its reliance on imported fossil fuels, offshore wind-powered H_2 production could play a pivotal role, provided that economic, technical, and policy barriers are effectively managed.

This study provides a comprehensive techno-economic analysis of green hydrogen production using offshore wind energy in Türkiye, but several limitations should be acknowledged. Variability in wind resources introduces fluctuations on daily, seasonal, and yearly scales that may not be fully captured, potentially leading to deviations from projected energy outputs. The cost components, including capital and operational expenditures, are based on current industry data, and future changes in technology costs, market conditions, or policy incentives could affect actual production costs. Assumptions regarding electrolyzer efficiency may not fully reflect real-world performance, as efficiency can vary depending on specific operating conditions and technological developments. Additionally, the analysis does not account for all infrastructure costs required to connect offshore wind farms to electrolysis facilities, such as subsea cables and compression stations. While the study's findings offer valuable insights for Türkiye, they may not be directly applicable to regions with different geographic, regulatory, or economic conditions. Finally, the economic feasibility of green hydrogen production is highly dependent on current government incentives, renewable energy policies, and carbon pricing, which could change in the future, impacting the cost competitiveness of green hydrogen.

5. Conclusion

In conclusion, this study offers a thorough analysis of the economic viability of green H_2 production from offshore wind in Türkiye, focusing on four key regions: Ayvacık, Bozcaada, Edremit, and Bandırma. The results highlight the significant impact of regional characteristics, such as wind capacity factors and CAPEX, on the LCOH. The initial conclusion reached is, Ayvacık emerges as the most cost-efficient location, with a capacity factor of 50.5% and an LCOH of $4.33/kg$H_2$ for alkaline electrolysis. In contrast, Bandırma, despite its highest installed wind capacity of 145 MW, incurs the highest LCOH at $5.85/kg$H_2$ due to a lower capacity factor of 34.6% and higher CAPEX. Secondly, the conclusion drawn is the analysis also underscores the economic performance of alkaline versus PEM electrolyzers. Alkaline electrolyzers demonstrate a specific energy consumption of 49.44 kWh/kgH_2, while PEM electrolyzers show a higher consumption of 50.56 kWh/kgH_2, resulting in PEM LCOH reaching up to $6.78/kg$H_2$ in Bandırma. However, PEM systems offer operational benefits such as faster start-up times and better integration with renewable energy sources. Thirdly, the study emphasizes the crucial role of policy support, illustrating that local content incentives can reduce the LCOH in Ayvacık from $5.15/kg$H_2$ to $4.13/kg$H_2$, showcasing the importance of government involvement in enhancing the competitiveness of Türkiye's green H_2 production.

The integration of desalination for electrolysis presents significant technological challenges that are critical in shaping the cost structure of green H_2 production. In regions with limited freshwater resources, the need for desalination increases both CAPEX and operational costs. This underscores the necessity for ongoing research and development aimed at optimizing desalination processes to enhance their energy efficiency and cost-effectiveness, particularly within green H_2 production systems. Offshore wind energy, with its stable and abundant output, holds substantial promise for scaling H_2 production to meet growing domestic and export demands. However, achieving this scale will require considerable investments in the infrastructure necessary for H_2 transport, storage, and distribution. The development of a robust H_2 supply chain will depend on collaborative efforts between public and private sectors, alongside international partnerships. In Türkiye, offshore wind-powered H_2 production represents a critical opportunity for the country's energy transition and decarbonization efforts. Regions such as Ayvacık, which benefit from favorable wind conditions, offer economically viable prospects for green H_2 generation, especially when supported by strong policy frameworks. As Türkiye strives to diversify its energy portfolio and reduce dependence on imported fossil fuels, offshore wind-generated green H_2 could significantly enhance energy security, stimulate industrial growth, and position the country as a leader in the global renewable energy market.

Future research should focus on technological advancements in both desalination and electrolysis, as well as the development of comprehensive policies that promote sustainable H_2 production. Additionally, infrastructure development will be key to ensuring the viability and scalability of green H_2 initiatives. With the right mix of innovation, policy support, and investment, offshore wind-generated green H_2 can become a cornerstone of Türkiye's sustainable energy future, driving economic growth and environmental sustainability.

CRediT authorship contribution statement

Yasemin Balcı: Writing – review & editing, Writing – original draft, Software, Resources, Methodology, Formal analysis, Data curation. **Celal Erbay:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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