

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL

**TECHNOECONOMIC INVESTIGATION OF HYDROGEN
PRODUCTION FROM ONSHORE WIND FARMS: A
FEASIBILITY ANALYSIS FOR TURKEY**

ELİF SERT ENGİN

**A THESIS OF MASTER OF SCIENCE
DEPARTMENT OF CHEMICAL ENGINEERING**

ADVISOR: PROF. DR. MURAT ÖZDEMİR

JULY 2025

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GEBZE TEKNİK ÜNİVERSİTESİ
LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

KARADAKİ RÜZGAR ÇİFTLİKLERİNDEN HİDROJEN
ÜRETİMİNİN TEKNO EKONOMİK İNCELENMESİ:
TÜRKİYE İÇİN BİR FİZİBİLİTE ANALİZİ

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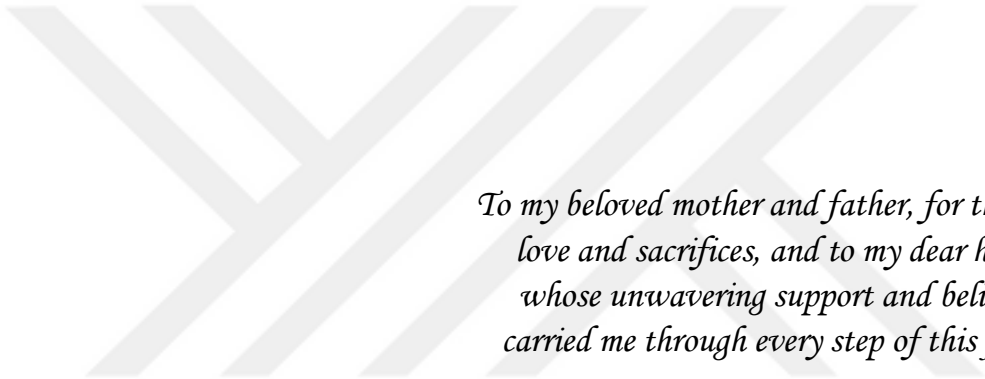
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*To my beloved mother and father, for their endless
love and sacrifices, and to my dear husband,
whose unwavering support and belief in me
carried me through every step of this journey...*

ABSTRACT

This thesis investigates the technoeconomic feasibility of green hydrogen production from onshore wind energy in Türkiye. A representative case study was carried out for Çanakkale, where wind speed data obtained from European Center for Medium-Range Weather Forecasts 5th generation reanalysis data set (ERA5) were modelled using three different probability distributions functions including Weibull, Rayleigh and Lognormal. Among these, Weibull distribution and Rayleigh distribution provided the best fit to local wind profile and Weibull distribution was used for further calculations. Three commercially available wind turbines were also compared, and General Electric (GE) 5.3-158 turbine was selected for calculations of annual energy production. It was estimated that the total annual wind energy production across Türkiye was approximately 226 TWh. Hydrogen production was estimated using a proton exchange member (PEM) electrolyzer, which operates at 65% efficiency for the estimations of current conditions. The modeling framework established in Çanakkale was then scaled to Türkiye using suitable land area data obtained from Türkiye Wind Energy Potential Atlas and assuming a turbine density of 5.3 MW/km². Under a zero-curtailment scenario, hydrogen production potential was estimated at 4.4 million tons/year, and it was observed that the electrolyzer was underutilized. With 20% curtailment scenario, electrolyzer utilization factors ranged between 71% and 98%. Highest performance for hydrogen production was observed for Marmara and Aegean regions. Levelized cost of hydrogen (LCOH) for each region was calculated and the values were in the range of 3.70 to 3.77 €/kg H₂ for the high performing cities. For 2035 and 2050 scenarios, values were in the range of 2.67 to 2.72 €/kg H₂ and 1.68 to 1.71 €/kg H₂, respectively. Overall, the findings indicate that Türkiye holds substantial potential for large-scale and cost-effective green hydrogen production through onshore wind energy integration, which is aligned with Türkiye's national roadmap and global targets.

Keywords: Wind Power, Wind to Hydrogen, Türkiye Green Hydrogen Potential, Türkiye Wind Energy.

ÖZET

Bu çalışma, Türkiye’de kara tipi rüzgâr enerjisine dayalı yeşil hidrojen üretiminin tekno ekonomik açıdan uygulanabilirliğini incelemektedir. Çalışmanın ilk aşamasında Çanakkale ili için bir vaka çalışması gerçekleştirilmiş; Avrupa Orta Vadeli Hava Tahminleri Merkezi 5. nesil yeniden analiz veri setinden (ERA5) elde edilen rüzgâr hızı verileri Weibull, Rayleigh ve Lognormal olmak üzere üç farklı olasılık dağılımıyla modellenmiştir. Bu dağılımlar arasında Weibull ve Rayleigh dağılımları yerel rüzgâr verilerine en uygun sonuçları vermiş; devam eden hesaplamalarda Weibull dağılımı kullanılmıştır. Ayrıca, üç farklı ticari rüzgâr türbini teknik özellikleri açısından karşılaştırılmış ve yıllık enerji üretimi hesaplamalarında General Electric (GE) 5.3-158 modeli tercih edilmiştir. Türkiye geneli için yıllık toplam rüzgâr enerjisi üretiminin yaklaşık 226 TWh olduğu hesaplanmıştır. Hidrojen üretimi, %65 verimlilikle çalışan bir proton geçirimli membran (PEM) elektrolizörü ile hesaplanmıştır. Çanakkale için geliştirilen modelleme yöntemi daha sonra Türkiye geneline uygulanmıştır. Bu süreçte Rüzgar Enerjisi Potansiyeli Atlası veri tabanından elde edilen arazi verileri ve 5.3 MW/km² türbin yoğunluğu varsayımı kullanılmıştır. Rüzgar enerjisinden üretilen tüm elektriğin hidrojen üretimi için kullanıldığı senaryoya göre yıllık hidrojen üretimi yaklaşık 4.4 milyon ton olarak hesaplanmıştır. Ancak bu durumda elektrolizör kapasitelerinin gerekli kapasiteden fazla olduğu gözlemlenmiştir. Bu nedenle, %20 enerji kesintisi senaryosu uygulanmış ve bu koşulda elektrolizör kullanım oranlarının %71 ile %98 arasında değiştiği belirlenmiştir. En yüksek hidrojen üretimi Marmara ve Ege bölgelerinde gerçekleşmiştir. Her bölge için seviyelendirilmiş hidrojen üretim maliyeti (LCOH) hesaplanmış; yüksek üretim kapasitesine sahip şehirlerde bu değer 3.70–3.77 €/kg H₂ aralığında bulunmuştur. 2035 ve 2050 yılı öngörülleri dikkate alındığında ise bu maliyetlerin sırasıyla 2.67–2.72 €/kg H₂ ve 1.68–1.71 €/kg H₂ seviyelerine düştüğü gözlenmiştir. Sonuçlar, Türkiye’nin kara tipi rüzgâr enerjisini kullanarak büyük ölçekte ve maliyet açısından rekabetçi bir şekilde yeşil hidrojen üretebileceğini göstermekte olup bu model hem ülkenin ulusal yol haritasıyla hem de küresel enerji dönüşümü hedefleriyle uyumlu bir çerçeve sunmaktadır.

Anahtar Kelimeler: Rüzgar enerjisi, Rüzgardan Hidrojen Üretimi, Türkiye Yeşil Hidrojen Potansiyeli, Türkiye Rüzgar Enerjisi.

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LIST OF SYMBOLS AND ABBREVIATIONS

A	:	Rotor swept area (m^2)
CF	:	Capacity Factor
c	:	Weibull scale parameter
H_2	:	Hydrogen
H	:	Annual hydrogen output (kg or Nm^3)
Gt	:	Gigaton
GWh	:	Gigawatt -hour
k	:	Weibull shape parameter
km	:	Kilometer
km^2	:	Square kilometer
kW	:	Kilowatt
kWh	:	Kilowatt-hour
m/s	:	Meters per second
Mt	:	Million tons
MW	:	Megawatt
MWh	:	Megawatt-hour
TWh	:	Terawatt-hour
Nm^3	:	Normal cubic meter
n	:	System life time (years)
O_2	:	Oxygen
OH^-	:	Hydroxide ion
P	:	Turbine power output (W)
Pt	:	Platinum
R^2	:	Coefficient of determination
t	:	Time (hours)
u	:	East-west direction wind speed
v	:	North-south direction wind speed
V	:	Wind shear exponent
α	:	Air density (kg/m^3)
ρ	:	Electrolyzer
el	:	Initial
i	:	Final
f	:	Used in electrolysis
used	:	Anion Exchange Membrane
AEM	:	Annual Energy Production
AEP	:	Application Programming Interface
API	:	AlkalineWaterElectrolysis
AWE	:	Windshearexponent
CAPEX	:	Capital Expenditure
CDS	:	Climate Data Store (Copernicus)
CRF	:	Capital Recovery Factor
EMRA	:	Energy Market Regulatory Authority (Türkiye)
ERA5	:	Fifth Generation ECMWF Atmospheric Reanalysis
EU	:	European Union
€/kgH ₂	:	Euros per kilogram of hydrogen

€/kW	:	Euros per kilowatt
€/MWh	:	Euros per megawatt-hour
GE	:	General Electric
GHG	:	Greenhouse Gas Emissions
GW	:	Gigawatt
HHV	:	Higher Heating Value
IEA	:	International Energy Agency
IEC	:	International Electrotechnical Commission
IEEFA	:	Institute for Energy Economics and Financial Analysis
IRENA	:	International Renewable Energy Agency
IRENEC	:	International Renewable Energy Conference
LCOE	:	Levelized Cost of Electricity
LCOH	:	Levelized Cost of Hydrogen
LHV	:	Lower Heating Value
MENA	:	Middle East and North Africa
Mt/year	:	Million tons per year
NREL	:	National Renewable Energy Laboratory
O&M	:	Operation and Maintenance
OPEX	:	Operational Expenditure
PEM	:	Proton Exchange Membrane
RMSE	:	RootMeanSquareError
SHURA	:	EnergyTransitionCenter
SOE	:	SolidOxideElectrolyzer
WPD	:	WindPowerDensity

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1. INTRODUCTION

In the face of accelerating climate change, rising energy demand, and the urgent need for decarbonization, the global energy landscape is undergoing rapid transformation. Among the emerging solutions, green hydrogen has gained prominence as a clean energy carrier that can contribute to the decarbonization of hard-to-abate sectors. Its production using renewable energy sources, particularly wind and solar power, offers a promising pathway toward carbon neutrality. Türkiye, with its abundant renewable energy potential and growing focus on hydrogen technologies, represents a strategic opportunity to diversify the energy mix, strengthen energy security, and support global climate objectives. This thesis examines the technoeconomic feasibility of hydrogen production from onshore wind in Türkiye by combining spatially resolved wind resource modeling with cost analysis to support evidence-based planning and policy development.

1.1. Background

Since the early 1990s, countries have been trying to find new ways to decrease greenhouse gas emissions (GHG) and tackle climate change. These efforts have resulted in major international agreements such as the Kyoto Protocol and the Paris Agreement [1]. Although such agreements continue to be signed and new targets are set, and despite significant reductions in GHG emissions by the European Union (EU), Russia, and the United States compared to 1990 levels, global GHG emissions reached an all-time high in 2023 at 53.0 Gt CO₂-equivalent. This represents a 1.9% increase compared to 2022 [2]. When considering energy and industrial emissions, energy-related CO₂ emissions increased by 1.1% globally in 2023, with coal accounting for 65% of this growth. Although this increase is concerning, the expansion of clean energy technologies has significantly limited the rate of growth. Without recent deployments of wind power, solar energy, nuclear power, heat pumps, and electric vehicles, global emissions would have increased at three times the observed rate [3].

Among clean energy sources, wind and solar power have been expanding rapidly [4]. However, key challenges remain, including energy storage, grid stability, and the

inability to meet demand during periods of insufficient generation [5]. In this context, hydrogen emerges as a promising solution. As the most abundant element in the universe, hydrogen possesses high energy content, nearly three times greater per unit weight than gasoline [6]. When produced using renewable electricity, such as from wind farms, hydrogen can be stored in pressurized or cryogenic tanks or transported via pipelines, trucks, trains, or ships [6].

Integrating hydrogen production with renewable energy sources like wind during periods of peak generation can help address intermittency issues while supporting the transition toward a green hydrogen economy [7]. The global momentum behind green hydrogen is growing, with countries such as Türkiye intensifying efforts to integrate hydrogen into their energy systems, complementing ongoing developments in renewable infrastructure [8].

Numerous studies emphasize the importance of hydrogen in the transition to a low-carbon energy system [9],[10]. Therefore, understanding different hydrogen production methods is of utmost importance. Method of hydrogen production influences the cost, scalability and the environmental impact. These methods can be classified into several categories that are often categorized by the feed used and the process employed. These technologies are identified with different colors as, brown or black, yellow, purple or pink, red, green, blue, white, aqua, turquoise and grey. Brown and black hydrogen refer to the production from coal and the type of coal used. Gasification technologies are used to produce hydrogen from coal and biomass. Yellow hydrogen is the method where hydrogen is produced by using electricity to carry out electrolysis. Pink hydrogen is the method where electricity from a nuclear power plant is used to produce hydrogen from water electrolysis. For purple hydrogen, a nuclear power plant, electrolysis and thermochemical water splitting is used. Red hydrogen is the one where high temperature splitting of water is used in high temperatures and a nuclear power plant is used as the energy source. Green hydrogen, in other words clean, renewable or low-carbon hydrogen is the one where water electrolysis is used in combination with the electricity produced from renewable sources. Blue hydrogen is again a low-carbon production method where fossil fuels are used with carbon capture, storage and utilization techniques. White hydrogen is the one where hydrogen is found in nature as free gas, meaning it is the one referring to naturally occurring hydrogen. Aqua hydrogen is developed in Canada and this method

allows extracting hydrogen from oil sands and oil fields; it can be a zero-carbon approach. Turquoise hydrogen uses methane and produces hydrogen via methane pyrolysis. Finally, grey hydrogen refers to the hydrogen that is produced from steam methane reforming, autothermal reforming or partial oxidation [11].

Among these, green hydrogen holds particular importance for sustainable energy transitions due to the growing availability of renewable energy sources such as onshore wind farms. To understand its role, current trends and future projections must be considered. According to the International Energy Agency (IEA), global onshore wind capacity grew by 382.7 GW between 2017 and 2022 and is expected to reach 846 GW by 2030. For offshore wind, cumulative capacity is projected to reach approximately 212 GW by the same year [12].

Regionally, China leads in installed wind capacity and is expected to add 360 GW of new capacity over a five-year period. In Europe, record levels of new installations are projected beginning in 2025, with Germany accounting for 26% of total onshore additions. Spain follows with 10%, while Türkiye and France each contribute 8%, and Finland and the UK 6%. Altogether, 93 GW of onshore wind capacity is expected to be added in Europe. North America is projected to add 71.5 GW, Latin America 28.7 GW, and Africa and the Middle East approximately 19 GW during the 2024–2028 period [13].

Türkiye has been making notable progress in developing its renewable energy capacity. As of September 2024, Türkiye's installed wind energy capacity reached 12.4 GW. The allocated capacity for wind is 26.1 GW, and the country's 2035 roadmap includes a target of 5 GW for offshore wind development [14]. These advancements align with Türkiye's renewable energy goal and wind is an important aspect of it. Integration of green hydrogen production with this wind energy potential could offer a solution to energy storage problems as well. A comprehensive assessment of Türkiye's onshore wind energy potential and green hydrogen production is essential to evaluate the feasibility and long-term sustainability of such projects. Technoeconomic analysis is a robust framework for assessing the economic performance of energy systems. It involves components such as process design, system modeling, capacity sizing, capital expenditure (CAPEX), operational expenditure (OPEX), and cash flow analysis [15].

1.2. Problem Statement and Objectives of the Study

The global energy sector is undergoing a rapid transformation in response to climate change, energy security concerns, and national decarbonization goals. Green hydrogen, produced through water electrolysis using renewable energy, is emerging as a key solution to achieving global net-zero emissions targets [16]. Despite its significant potential, the levelized cost of hydrogen (LCOH) remains higher than that of fossil-based hydrogen, presenting a major barrier to its widespread adoption [17].

Türkiye, with its growing energy demand, strategic geographical position, and considerable renewable energy potential, stands at a critical crossroads. As of September 2024, Türkiye's installed wind power capacity reached 12.4 GW; however, the application of this capacity for green hydrogen production remains largely unexplored at the national scale [18]. Furthermore, regional wind variability, seasonal fluctuations, and cost-performance dynamics of wind-to-hydrogen systems pose substantial challenges to their technoeconomic viability.

While the existing literature primarily focuses on either wind energy or hydrogen production individually, there is a notable lack of integrated, spatially resolved models that examine the interaction between wind energy and hydrogen production across Türkiye [19],[20]. Moreover, there is limited guidance on regional prioritization for green hydrogen production using onshore wind energy, leaving policy makers and investors without data-driven tools at the national level for decision making [21].

This thesis addresses these critical gaps by developing a technoeconomic modeling framework that combines wind resource assessment, seasonal energy yield estimation, and electrolyzer performance analysis to evaluate the feasibility of hydrogen production from Türkiye's onshore wind potential.

The main objective of this study was to assess the technoeconomic feasibility of green hydrogen production from onshore wind energy in Türkiye by developing and implementing an integrated, spatially resolved wind-to-hydrogen modeling framework. To achieve this, the spatial and temporal wind energy potential across all provinces of Türkiye were evaluated using ERA5 reanalysis data, and adjusted based on national sources to improve accuracy. Seasonal and annual wind power outputs were estimated through Weibull distribution fitting, and applied in conjunction with

selected wind turbine power curves. The production of green hydrogen and the associated energy curtailment were further modeled under both standalone and integrated wind-to-hydrogen system configurations. This modeling approach was then scaled nationally to capture regional variations in hydrogen yield and cost performance. Finally, the most promising regions for green hydrogen production were identified, generating policy-relevant insights to support strategic planning and investment.



2. LITERATURE REVIEW

This chapter reviews the existing literature on wind energy, hydrogen production models, and their technoeconomic integration. The aim was to identify relevant methodologies, assess case studies, and highlight key insights that inform the direction of this study. By evaluating current academic perspectives, the chapter establishes the conceptual and methodological foundation upon which the proposed modeling framework is built.

2.1. Hydrogen Production and Global Trends in Technoeconomic Analysis

The continuous growth of global population, industrial activity, and energy demand is placing increasing pressure on existing energy systems, which remain predominantly reliant on fossil fuels [22], [23]. Simultaneously, climate change has become a pressing global concern, prompting the adoption of international agreements such as the Paris Agreement, which require deep decarbonization strategies across nearly all sectors [24]. In this context, hydrogen is emerging as a key energy vector capable of contributing to decarbonization in hard-to-abate sectors such as steel production, fertilizer manufacturing, heavy transportation, and energy storage applications [25].

Hydrogen production pathways are typically classified based on their energy source and production process. Grey and blue hydrogen are both produced through steam methane reforming; however, grey hydrogen results in direct CO₂ emissions, whereas blue hydrogen incorporates carbon capture and storage (CCS) techniques to mitigate emissions. Brown hydrogen relies on coal gasification and syngas processing. Yellow hydrogen is produced via electrolysis using grid electricity, while turquoise hydrogen is obtained through methane pyrolysis. Pink hydrogen involves electrolysis powered by nuclear energy. In contrast, green hydrogen is produced through water electrolysis using electricity generated from renewable energy sources such as wind or solar power [26].

Driven by global decarbonization efforts, momentum is rapidly building around green hydrogen development. More than 50 countries have published national hydrogen

strategies, outlining targets for pilot programs and utility-scale deployment [27]. Despite these commitments, several challenges hinder the widespread adoption of green hydrogen, particularly high production costs, limited technology readiness, and integration barriers with variable renewable energy sources. As a result, the levelized cost of hydrogen (LCOH) for green hydrogen remains significantly higher than that of grey hydrogen. However, optimistic cost-reduction projections are linked to economies of scale, improvements in electrolyzer technologies, and falling renewable energy costs due to ongoing technological advancements [28].

To evaluate the economic and technical viability of hydrogen deployment, technoeconomic analyses are essential. LCOH estimates typically consider CAPEX, OPEX, system lifetime, conversion efficiency, and electricity input profiles. Advanced approaches incorporate hourly variability in renewable energy supply to capture the impacts of curtailment and system integration constraints more accurately [29].

Recent modeling trends emphasize data-driven frameworks with spatial and temporal resolution. These approaches are increasingly recognized as critical tools for policymakers and investors, helping to identify optimal deployment strategies, inform infrastructure planning, and evaluate scalability of green hydrogen systems.

2.2. Progress in Wind Energy and Hydrogen Integration

One of the earliest documented efforts to generate electricity from wind power was made by James Blyth, who constructed a small-scale wind turbine in Scotland in 1887 to supply electricity to his summer home[30]. This pioneering development was followed by more technically advanced experiments, notably those of Poul LaCour in Askov, Denmark during the 1890s, and later by the Putnam wind turbine project in the United States during the 1940s. Notably, LaCour utilized electricity generated from wind turbines for water electrolysis, producing hydrogen. His work laid the groundwork for the wind-to-hydrogen concept, introducing not only technical innovation but also early socio-technical thinking in renewable energy systems [31].

In the early 2000s, the U.S. National Renewable Energy Laboratory (NREL) launched the “Wind2H₂” project, which significantly influenced the design of modern wind-to-hydrogen systems [32]. This project integrated wind turbines with both PEM and alkaline electrolyzers to produce hydrogen from renewable energy sources. Through

advancements in power electronics and system optimization, the project achieved a reduction in hydrogen production costs from \$6.23/kg H₂ to \$5.83/kg H₂. While this remained above the U.S. Department of Energy's (DOE) 2012 target of \$3.10/kg H₂, the study marked a significant step forward in demonstrating the feasibility and cost-reduction potential of such systems [32].

Technically, wind-to-hydrogen systems consist of four main components: wind turbines, power electronics, electrolyzers, and hydrogen storage units [33]. Although various types of electrolyzers are commercially available, their ability to adapt to the fluctuating output of wind power is a key consideration. For hydrogen storage, pressurized vessels are commonly used, although emerging technologies such as metal hydrides are being explored, requiring detailed cost-performance analyses to assess their viability [34]. In parallel, offshore wind-to-hydrogen systems are also gaining attention. Studies have shown that integrating hydrogen production with offshore power infrastructure can reduce production costs to as low as €2.4/kg H₂ [35].

From a community-scale perspective, the Lolland pilot project in Denmark stands out as a notable example of decentralized wind-to-hydrogen application. Recognized as Denmark's first hydrogen-based community powered by both onshore and offshore wind turbines, Lolland represents a successful case of using renewable energy for hydrogen production and storage at a local scale. The project serves as a model for long-term, climate-resilient investment strategies and demonstrates the potential of community-driven energy solutions [36].

2.3. Technoeconomic Assessment for Hydrogen Production

Technoeconomic assessments for hydrogen production technologies are essential tools used to compare system costs, guide research funding priorities, and shape strategies aimed at reducing overall production expenses [37]. A technoeconomic assessment evaluates the economic performance of a given process through a structured analysis. Typically, this involves four key stages. First, system modeling is conducted, in which the overall configuration—including wind turbines, power conversion systems, electrolyzers, and hydrogen storage—is defined, often through a process flow diagram. Second, energy modeling is carried out to map energy flows and identify potential efficiency improvements. This is followed by cost modeling, where CAPEX, OPEX,

equipment sizing, maintenance costs, and all other relevant cost inputs are quantified. Lastly, economic analysis is performed using financial indicators such as the Levelized Cost of Energy (LCOE) and Levelized Cost of Hydrogen (LCOH), which allow for comparative evaluation across technologies and configurations [38].

To develop a comprehensive technoeconomic model, the system design must first be clearly defined, including the sizing of components such as turbine power rating, electrolyzer capacity, and hydrogen storage volume. Once these parameters are established, they are integrated with cost models to form the basis of economic performance evaluation [39]. In recent studies, LCOH has emerged as a widely accepted metric for comparing hydrogen production systems and assessing their economic viability. LCOH can be expressed either in terms of cost per unit of energy generated or cost per unit of hydrogen mass produced. It represents the discounted lifetime cost of the facility, incorporating all expenditures over the operational period of the system [39]. Furthermore, the LCOH approach allows for sensitivity analysis with respect to variables such as wind power availability, curtailment effects, and even geographic landscape factors, offering a robust method to evaluate the feasibility of proposed hydrogen production systems.

2.4. National Case Studies

In recent years, the interest in green hydrogen production in Türkiye has also grown significantly, driven by the national goals towards decarbonization. These studies have focused on renewable energy-based hydrogen production potential in Türkiye, explored resource availability, production technologies and conceptual planning for hydrogen hubs. However, their depth, methodology and spatial granularity vary considerably.

Dincer et al. (2021) proposed the hydrogen farm concept for Türkiye [41]. Their study evaluated hydrogen production potential across all provinces by integrating multiple energy sources including onshore and offshore wind, solar PV, geothermal and biomass sources as well as hydroelectric power. Using land use data and exclusion criteria developed by official sources, the usable areas for renewable energy deployment were calculated, assuming the energy output was directed to alkaline electrolysis systems for hydrogen generation [40]. In their study, only one turbine type,

Vestas V90-2.0 MW was used. Although their study provides a valuable top-down perspective and introduces a multisource planning approach, wind energy modeling was based on static wind speed maps at 50 m height without seasonal resolution or hub-height correction, monthly or seasonal wind variability was not considered, economic feasibility was not assessed, and operational details of the electrolyzer model were not given.

Karayel et al. (2023) conducted a national-scale assessment of green hydrogen production potential in Türkiye using onshore wind, offshore wind, and undersea current resources. The study employed a proton exchange membrane (PEM) electrolyzer to model hydrogen production and estimated a total national potential of 248.56 million tons of hydrogen, of which 233.38 million tons were attributed to onshore wind alone [41]. A single wind turbine model, the Vestas V90-2.0 MW, was applied across all locations. However, the analysis did not account for seasonal wind variations, and no economic inputs or cost evaluations were provided.

Gulay et al. (2025) evaluated modular electrolyzer operation in İzmir using wind and solar sources. They compared different power allocation strategies and electrolyzer types for a 10 MW green hydrogen plant and emphasized the importance of electrolyzer sizing and power input characteristics in optimizing LCOH. By reducing the electrolyzer capacity, they showed a decrease in LCOH [42]. Although they showed how LCOH responds to optimization strategies, their study was limited to four locations in İzmir. They used only 2019 data for wind speed from MERRA-2. Their turbine selection was limited to Vestas V90-2.0 MW.

Güven and Kayalica (2025) evaluated Türkiye's green hydrogen potential using a spatially resolved model integrating climate projections, life cycle assessment and life cycle cost assessment for a 10 MW PEM electrolyzer system powered by combinations of solar PV and wind. They used a Vestas V126-3.0 MW turbine and obtained the lowest LCOH for Aegean and Marmara regions, ranging from \$2.25 to \$7.01/kg H₂ [43]. Curtailment and electrolyzer utilization options were not given, and seasonal output was not shown. In addition, land considerations were not given in detail.

Balci and Erbay (2025) evaluated the economic feasibility of green hydrogen production from offshore wind energy in Türkiye for four regions including Ayvacık, Bozcaada, Edremit and Bandırma. They developed a technoeconomic model for

hydrogen production using 50 MW alkaline and PEM electrolyzers. For offshore wind, Ayvacık had the lowest LCOH at \$4.33/kg H₂, which was improved to \$4.13/kg H₂ with local content incentives. They reported that PEM offers operational benefits [44].

2.5. International Case Studies

Aligned with national decarbonization strategies, green hydrogen production from renewable energy sources has emerged as a key instrument in the global energy transition. As a result, many countries have begun testing various technological configurations to evaluate feasibility under different conditions. In particular, the integration of electrolyzer technologies with wind and solar power has attracted increasing interest due to its potential for cost-effectiveness and technical adaptability. Case studies from diverse geographic contexts are especially valuable for assessing the scalability and applicability of renewable-to-hydrogen systems. Table 1 presents selected case studies from different countries that explore such integrated models. These examples highlight anticipated technological advancements and their influence on LCOH, offering a useful reference framework for model development.

Table 2.1: Case studies for renewables to hydrogen models.

Country/Project	Energy Source	Electrolyzer Technology	Scale	LCOH
Saudi Arabia [45]	Wind Solar	PEM	Utility	\$3.27-\$12.12/kg H ₂ (2024)
Wind Float Portugal [46]	Offshore Wind	PEM	Demo	€4.25-€8.47/kg H ₂ (2019)
China [47]	Offshore Wind	Alkaline PEM Solid Oxide	National Commercial	\$2.7- \$4.0/kg H ₂ (2030)
Queensland Australia [48]	Wind Solar	PEM	Regional	\$3.1- \$3.7/kg H ₂ (2030)
Poland [49]	Offshore wind	PEM		€3.60- €3.71/kg H ₂ (2030)

3. METHODOLOGY

In this chapter, the methodological framework was outlined. Detailed data sources, modeling techniques, key assumptions, and analytical tools used in the study were presented. The approach was structured to ensure accuracy and scalability, allowing for location-specific insights and system-wide analysis.

3.1. Research Design and Approach

In this study, a quantitative research approach was applied to develop a spatially resolved technoeconomic model. The feasibility of green hydrogen production from onshore wind energy in Türkiye was evaluated. The research integrated wind resource assessment, seasonal energy modeling, hydrogen production simulation, and cost estimation within a unified framework.

The study followed a two-stage design approach. In the first stage, a detailed case study was conducted for Çanakkale, which was selected due to its high wind energy potential. This stage served as the development and validation phase for the model. Wind speed data obtained from ERA5 reanalysis were fitted to three different probability distributions to identify the best-fitting model for national-scale application. The monthly Weibull probability density function was then applied to the corrected wind speed data, a widely used and well-established method in wind resource assessment [50], [51]. Three commercially available wind turbines were compared based on their energy production potential and the resulting LCOE. The estimated energy output from the selected turbine was used to model hydrogen production via PEM electrolyzers, assuming a system efficiency of 65%, consistent with benchmark values reported in the literature [28]. Both standalone (one turbine, one electrolyzer) and integrated system scenarios were examined to analyze layout-driven variations in economic performance. In the second stage, the validated model was scaled up to the national level. For all provinces of Türkiye, available land areas were identified, and the same modeling framework was applied using ERA5 wind data. The resulting wind power estimates were then used in the hydrogen production model to generate city-level projections of hydrogen yield, curtailment, and LCOH.

3.2. Data Sources and Selection Criteria

In this study, secondary data sources were utilized to build the technoeconomic model. Data collection was focused on three main categories: technical, economic, and country-specific data. These datasets formed the foundation of the research. Technical data included wind resource data [50], turbine specifications [51], and electrolyzer parameters [28], [52]. Economic data comprised CAPEX and OPEX values [53], [54], [55], as well as hydrogen pricing trends [52], [56], [57]. Country-specific information included national hydrogen roadmaps, which were obtained from [8].

For data validation, wherever possible, data were cross validated using multiple sources to ensure reliability. In cases where specific data was not available, regional or global averages were used, and sensitivity analyses were applied to account for uncertainties.

3.3. Technoeconomic Modeling Framework

The steps followed in the technoeconomic modeling framework for wind-to-hydrogen system design in Türkiye were illustrated in Figure 1. For wind energy modeling, ERA5 hourly reanalysis data were collected for the period from January 2021 to December 2024 and adjusted to represent wind speeds at a hub height of 100 meters. Using the average wind speed data, the hourly values were corrected, and wind speed distributions were fitted to the Weibull probability density function to capture seasonal variability. These distributions were then used to calculate the frequency of wind speeds in 0.5 m/s intervals for each month.

In the turbine energy output modeling stage, the wind speed bins were linked to expected power output using manufacturer supplied power curves. For each bin, energy production was calculated and summed up to determine the annual energy output. This step was first applied in detail for the province of Çanakkale using three candidate turbines: GE 5.3-158 (5.3 MW, 158 m rotor diameter), Nordex N131/3600 (3.6 MW, 131 m rotor), and GE 2.75-103 (2.75 MW, 103 m rotor). Based on performance criteria, the GE 5.3-158 turbine was selected for national scale modeling. Turbine siting density was fixed at 5.3 MW/km² in accordance with national planning assumptions [58].

For hydrogen production modeling, the calculated electrical energy output from turbines was converted into hydrogen using a PEM electrolyzer system with an assumed efficiency of 65%. Two system layouts were modeled for Çanakkale: a standalone configuration (one turbine coupled with one electrolyzer) and an integrated scenario in which the total city-level wind capacity was used to feed a centralized electrolyzer hub.

In the economic modeling phase, both LCOE and LCOH were calculated for each city using a discounted cash flow approach. This analysis included capital and operational expenditures for wind turbines and electrolyzer units, assuming a project lifetime of 25 years and a discount rate of 8%. The LCOH results were expressed in €/kg H₂. Economic parameters were derived from internationally recognized sources, including reports from the International Renewable Energy Agency (IRENA), the International Energy Agency (IEA), and the Hydrogen Council.

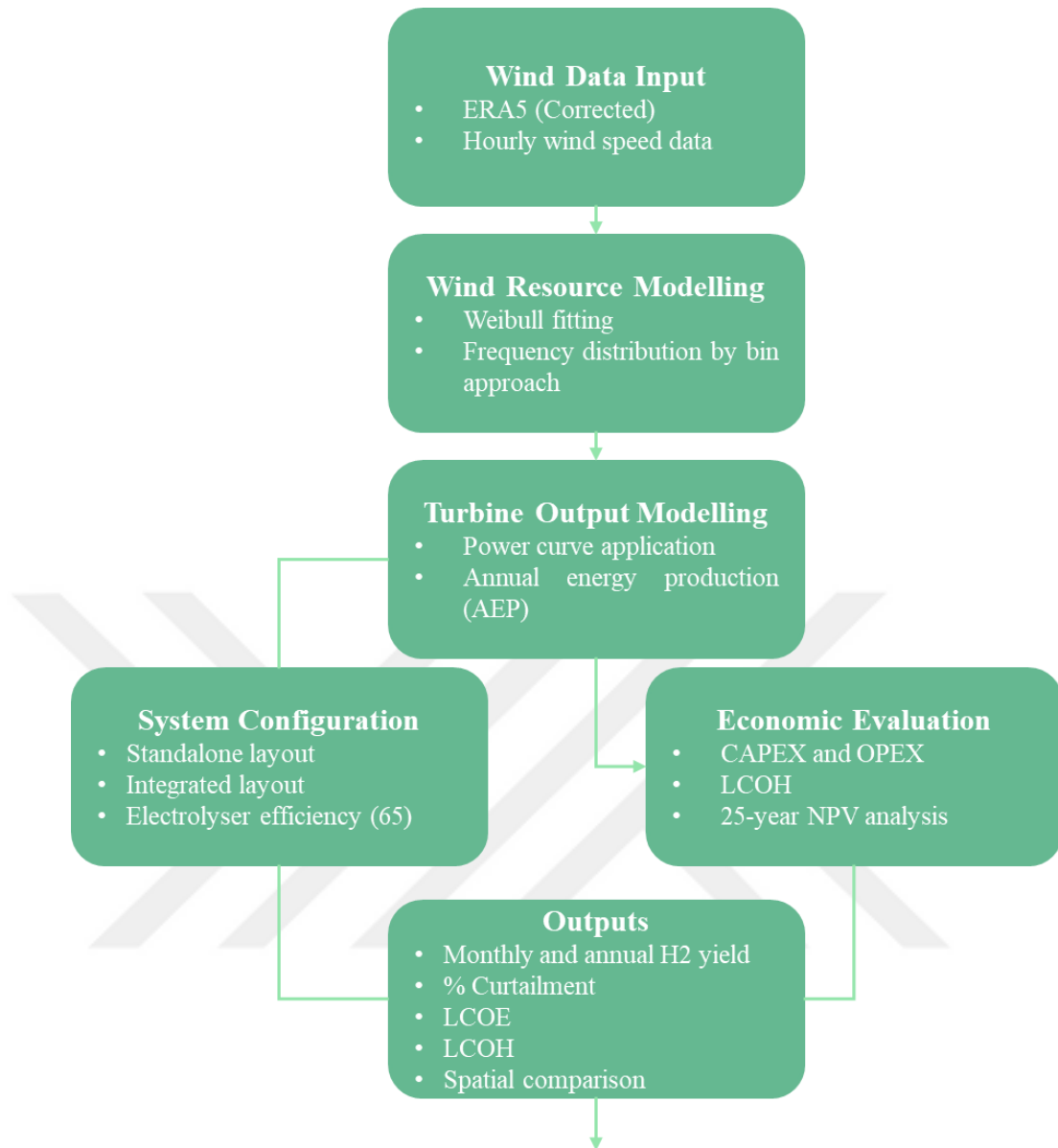


Figure 3.1: Overview of the technoeconomic modeling framework.

3.4. Analytical Tools and Techniques

Several tools were employed for data processing, simulation, and analysis in the implementation of the modeling framework. Python (version 3.11, Python Software Foundation, USA) was used to develop custom scripts for acquiring and structuring ERA5 wind data for wind resource modeling across all cities. Hourly wind data were obtained from the ERA5 reanalysis dataset, which provided wind components (u and v) at 10 meters above ground level. Using the cdsapi and xarray packages, a custom script was developed to extract hourly data from the Copernicus Climate Data Store

API for each provincial capital in Türkiye. The resulting datasets were saved in Microsoft Excel (version 2506, Microsoft Corporation, Redmond, WA, USA) for further wind speed analysis and modeling. The wind speed at 10 meters were calculated for each hour using the standard formula given below:

$$V = \sqrt{u^2 + v^2} \quad (3.1)$$

To obtain wind speeds at hub height, the 10 m data were extrapolated using power law:

$$V_{100} = V_{10} \left(\frac{100}{10} \right)^\alpha \quad (3.2)$$

where the wind shear exponent was set to 0.143, representing neutral atmospheric stability.

A bias correction was performed to each city's hourly 100 m time series. This was done by comparing average wind speed data calculated with the average wind speed data obtained from national resources. The correction factor was calculated as:

$$\text{Correction Factor} = \frac{V_{REPA}}{V_{ERA5}} \quad (3.3)$$

Each hourly data was then adjusted by:

$$V_{100,corrected}(t) = V_{100}(t) * \text{Correction factor} \quad (3.4)$$

This corrected series formed the basis for modeling. For visualization, Excel's chart tool was used, and the Solver add-in was employed for electrolyzer capacity optimization.

4. TECHNICAL MODELING CASE: ÇANAKKALE

Technical modeling of the wind-to-hydrogen system at the selected site, Çanakkale, was presented in this chapter. A detailed assessment of wind resource availability, turbine performance, hydrogen production calculations, and system integration parameters was introduced. The purpose was to establish a high-resolution case study to form the basis for scaling the model to the national level in Türkiye. Wind data, along with technoeconomic parameters from well-established and widely recognized sources, were used to reflect real-world conditions.

4.1. Wind Resource Assessment

Evaluating the technical feasibility of hydrogen production via wind-powered electricity required a thorough wind resource assessment. Therefore, the accuracy and reliability of the input wind data directly impacted the precision of energy yield estimations, and consequently, the hydrogen output and cost projections. In this section, the sources used for wind data, the methodology applied for hub height adjustment, and the approach used for capacity factor estimation together with the underlying rationale were presented.

4.1.1. Data Sources and Selection Criteria

As mentioned earlier, accurate wind data was critical for modeling the energy production potential of onshore wind farms and linking it to hydrogen production potential. In this section, the main sources used to gather wind data for Türkiye were outlined, along with the selection criteria applied to identify high-potential sites across the country. Table 2 presents the data sources used to collect wind information, estimate wind capacity, and determine key parameters for technoeconomic analysis. The Global Wind Atlas and Türkiye Wind Energy Potential Atlas were specifically selected due to their high spatial resolution and accessibility. ERA5 data was also included for its long-term hourly time series, which supported the analysis of seasonal and temporal variability. While these datasets were well suited for macro-scale

assessments, site-specific wind measurements might still be necessary for detailed project development.

Table 4.1: Data sources.

Source	Provider/Organization	Type of Data	Purpose of Use in Current Study
ERA-5	European Centre for Medium-Range Weather Forecasts	Hourly wind speed components	Wind speed data for each city
Türkiye Wind Energy Potential Atlas	Ministry of Energy, Türkiye	National wind potential maps	Validation for ERA-5 data
IRENA Reports	International Renewable Energy Agency	Reports on global wind energy trends	Validation of assumptions for capacity factors, CAPEX, OPEX, hydrogen cost
IEA Reports	International Energy Agency	Market outlooks, capacity factor data, global wind and hydrogen integration data	Technoeconomic modeling references and comparison of global sites
IEEFA Reports	Institute for Energy Economics and Financial Analysis	Financial analysis of renewables	Türkiye's renewable transition trajectory contextualizing
EMRA Data	Türkiye's Energy Market Regulatory Authority	National Energy Statistics and licensing data for wind farms	Case study validation and regulatory references
IRENEC Papers	International Renewable Energy Conference, Türkiye	Papers and case studies focused on Türkiye's renewable sector	Referring local academic and policy papers

To obtain an accurate model, a suitability criterion was applied to evaluate the wind data gathered for this study. According to the Ministry of Energy and Natural Resources, areas within Türkiye with elevations ranging from 0 to 3000 meters and average annual wind speeds exceeding 6.5 m/s at 100 meters are considered suitable for the deployment of onshore wind farms. Based on this criterion and an assumed turbine density of 5.3 MW/km², Türkiye's total onshore wind potential was estimated at 57,786 MW [59].

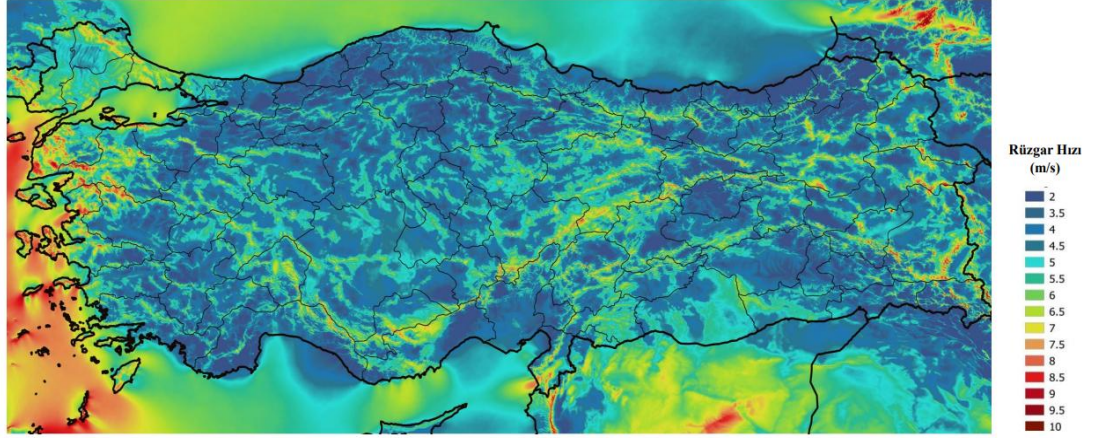


Figure 4.1: Annual wind speed distribution in Türkiye [59].

4.1.2. Selection of Representative Case Site

A single high-potential onshore wind site was selected as a representative case to conduct technical modeling and hydrogen production analysis in this study. The aim of this approach is to enable detailed and location-specific modeling while maintaining a scalable framework that can be extended to the national level for Türkiye.

To identify the case site, average wind speed, capacity factor, and power density at 100 meters across Türkiye's regions were compared to determine the areas with the highest potential. Türkiye's Wind Energy Potential Atlas was used for this comparison, and Table 3 summarizes the key regional data.

Table 4.2: Regional wind energy potential in Türkiye at 100 m [59].

Region	Average Wind Speed (m/s)	Capacity Factor (%)	Power Density (W/m ²)
Aegean	4.81	21.3	176.890
Marmara	5.24	25.7	201.765
Southeastern Anatolia	4.59	18.6	137.229
Mediterranean	4.46	18.3	162.194
Central Anatolia	4.53	17.3	128.537
Eastern Anatolia	4.61	18.4	152.670
Black Sea	4.01	14.4	121.152

The Marmara and Aegean regions exhibit the highest wind performance among Türkiye's seven regions. Specifically, the Marmara region leads with an average wind

speed of 5.21 m/s, a capacity factor of 25.7%, and a power density of 201.77 W/m². The Aegean region follows closely with a wind speed of 4.81 m/s and a capacity factor of 21.3%. To narrow down potential case study sites, cities within the Aegean and Marmara regions were compared based on key wind metrics. Table 4 presents data for 19 cities in these regions, including their respective average wind speeds, capacity factors, and power densities.

Table 4.3: Wind resource by city in Marmara and Aegean Regions at 100 m [59].

City	Region	Average Wind Speed (m/s)	Capacity Factor (%)	Power Density (W/m ²)
İstanbul	Marmara	5.79	0.30	218.216
Tekirdağ	Marmara	5.67	0.29	205.710
Edirne	Marmara	5.58	28.20	216.740
Kırklareli	Marmara	5.51	27.08	212.170
Balıkesir	Marmara	5.43	28.10	236.382
Çanakkale	Marmara	6.14	34.63	305.250
Bursa	Marmara	4.30	17.90	145.580
Bilecik	Marmara	4.11	14.60	108.654
Sakarya	Marmara	3.95	14.67	108.570
Kocaeli	Marmara	4.41	16.94	117.940
Yalova	Marmara	4.84	22.10	182.189
İzmir	Aegean	5.66	30.40	277.168
Manisa	Aegean	4.62	20.42	160.100
Aydın	Aegean	4.59	20.10	165.586
Uşak	Aegean	4.68	19.31	132.640
Kütahya	Aegean	4.63	18.05	133.550
Afyon	Aegean	4.76	19.23	153.070
Denizli	Aegean	4.13	15.01	117.960
Muğla	Aegean	8.39	18.40	164.904

Çanakkale demonstrated the strongest wind performance among the evaluated cities, with a capacity factor of 34.6% and a power density of 305 W/m². İzmir followed closely with slightly lower wind metrics. In addition to its excellent wind profile, Çanakkale was selected in this study as the case site for technoeconomic modeling of wind-based hydrogen production. The province is also part of Türkiye's first Hydrogen Valley project, launched in 2023 under the coordination of the South Marmara Development Agency [60]. This designation reinforced Çanakkale's strategic importance within Türkiye's hydrogen roadmap, making it a highly relevant location for integrated energy modeling.

According to the Wind Resource Assessment Handbook published by the National Renewable Energy Laboratory (NREL), Class 4 and higher wind areas are generally favorable for most wind turbine applications. Class 3 areas may also be viable for wind

energy development when tall turbines are used, while Class 1 areas are considered unsuitable for utility-scale projects [61]. Table 5 presents wind speed and wind power density values at a reference height of 10 meters to determine wind class classifications for the selected site.

To determine the wind power class of the Çanakkale region, it was necessary to adjust the known wind speed to a reference height. For this purpose, the power law equation was used.

$$V_2 = V_1 x \left(\frac{z_2}{z_1} \right)^\alpha \quad (4.1)$$

where V_1 is the known wind speed at the measurement height z_1 , V_2 is the wind speed to be determined, and α is the wind shear exponent generally taken as 0.143 [61].

For Çanakkale, the wind speed at 100 meters was obtained from ERA5 as 6.18 m/s. The average wind speed at 100 meters based on national sources was reported as 6.14 m/s. Since ERA5 is a reanalysis dataset and is known to contain biases due to its coarse spatial resolution and inability to resolve local variations [50], a simple correction method was applied to ensure alignment with national datasets [62].

$$V_{100 \text{ meters}} = V_{100 \text{ meters, ERA5}} \frac{V_{avg, 100 \text{ meters REPA}}}{V_{avg, 100 \text{ meters ERA5}}} \quad (4.2)$$

4.2. Comparison of Probability Density Functions

The probability distribution of wind speeds for the case site was analyzed using three different models: the Weibull distribution, Rayleigh distribution, and Lognormal distribution. These models were selected due to their widespread use in the literature and their demonstrated ability to effectively capture wind behavior [63].

Root Mean Square Error (RMSE) and the Coefficient of Determination (R^2) were used to compare the performance of the selected models to the observed distribution.

Before fitting model functions to the actual wind speed data of the case site, an observed distribution was created. Hourly wind speed measurements for Çanakkale

were grouped into intervals, referred to as wind speed bins, and the frequency of each bin was calculated using Microsoft Excel. Wind speeds were binned in intervals of 0.5 m/s to enable compatibility with turbine power curves provided by manufacturers.

The number of observations in each bin was counted, and the relative frequency of each bin was determined by normalizing the bin counts by the total number of observations. These results were used to construct the observed probability distribution, which served as a baseline for comparison with fitted models..

Two parameter Weibull distribution is widely used in wind energy studies, and it is flexible enough to use in different wind regimes. Two parameter Weibull distribution is given by [64]:

$$f(V) = \frac{k}{c} \left(\frac{V}{c}\right)^{k-1} \exp \left[-\left(\frac{V}{c}\right)^k \right] \quad (4.3)$$

where $f(V)$ is the probability of the wind speeds (V) observed, k is the dimensionless Weibull parameter, named as shape parameter, and c is the Weibull scale parameter (m/s).

For the calculation of these Weibull parameters, there are couple of methods introduced in literature. Empirical Method of Justus, Moment Method (Standard Deviation Method), Power Density Method, Maximum Likelihood Estimation and Least Squares Method are some examples to the methods for calculation of the parameters. Although there are different studies showing how each method works, there is no consensus on which one fits better [65].

The Empirical Method of Justus is very similar to the Moments Method. In this method, the standard deviation of the wind speeds for the selected region was considered to calculate the shape parameter and scale parameter was calculated by the same formula that was used in Moments Method [66]. The shape parameter is calculated with the following equation [66].

$$k = \left(\frac{\sigma}{V_m} \right)^{-1.086} \quad (4.4)$$

where σ is the standard deviation of the dataset, and v_m is the mean average wind speed.

The scale parameter was calculated with the below equation [66].

$$c = \frac{V_m}{\Gamma\left(1 + \frac{1}{k}\right)} \quad (4.5)$$

where Γ is the gamma function.

Rayleigh distribution only utilizes one parameter, the mean wind speed. It is also a special case of Weibull distribution when $k=2$ [63].

Rayleigh distribution was given by [67]:

$$f(V) = \frac{\pi}{2} \left(\frac{V}{V_{avg}^2} \right) \times \exp\left(-\frac{\pi}{4} \left(\frac{V}{V_{avg}} \right)^2\right) \quad (4.6)$$

Lognormal distribution was given by [68]:

$$f(V) = \frac{1}{x * \sigma \sqrt{2\pi}} * \exp\left(-\frac{1}{2\sigma^2} (\log(x) - \mu)^2\right) \quad (4.7)$$

Parameters of the lognormal distribution were calculated as follows [69]:

$$V_x = \frac{\text{Standard deviation}}{\text{Average wind speed}} \quad (4.8)$$

$$\sigma_{\ln(X)} = \sqrt{\ln(V_x^2) + 1} \quad (4.9)$$

$$\mu_{\ln(x)} = \ln(\text{Average wind speed}) - \frac{1}{2} \sigma_{\ln(X)}^2 \quad (4.10)$$

Figure 4.2 shows the performance of the fitted Weibull, Rayleigh and Log-normal functions compared to the observed frequency at the case site. Both Weibull and

Rayleigh functions showed a great fit compared to Log-normal distribution function. These results are also consistent with the calculated R^2 values.

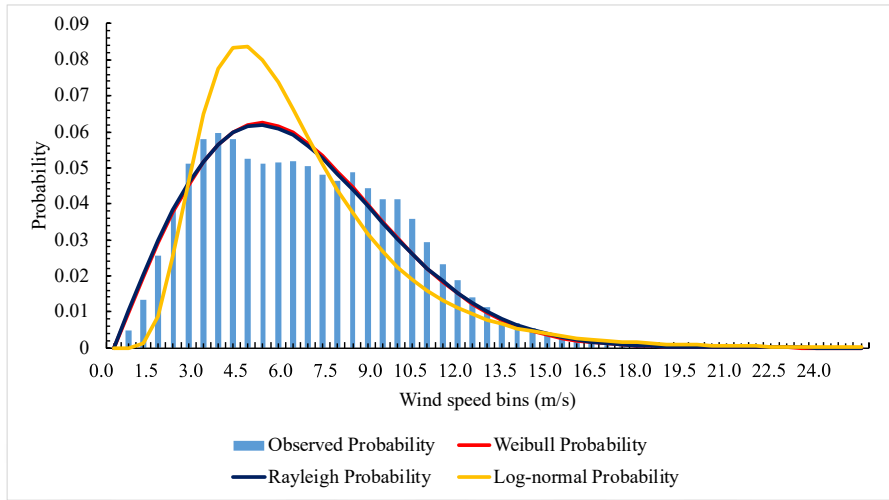


Figure 4.2: Comparison of probability function performance.

The root means square error and R^2 values were calculated for each model. Table 4.4 gives an overview of the values used for the comparison of the methods. Both Weibull and Rayleigh methods gave R^2 value of 0.96. In contrast, Log-normal method showed a poor performance which indicates the inadequacy of the method to capture wind regime characteristics of the case site. As mentioned, Rayleigh is a special form of Weibull with shape parameter equal to 2. The shape parameter calculated for case site was very close to 2 ($k=2.026$) hence, Rayleigh is also showed a great fit for Çanakkale.

Table 4.4: Comparison of models for wind speed probability calculation.

Model	R^2	RMSE	Fit quality
Weibull	0.96	0.0045	Great fit
Rayleigh	0.96	0.0044	Great fit
Log-mean	0.76	0.0107	Poor fit

Among the three distribution functions, the Weibull distribution was selected for modeling. In addition to providing a strong fit for the case site, the Weibull function offered greater flexibility compared to the Rayleigh distribution, as it incorporated the shape parameter k rather than assuming it as a fixed constant. The inclusion of the shape parameter allowed the model to adapt to varying wind regimes, which was particularly important for scaling the analysis across different cities in Türkiye.

4.3. Wind Power Density and Energy Potential

Wind power density (WPD) is one of the key indicators of the available kinetic energy in the wind per unit area. It serves as a tool to evaluate the site's suitability for potential projects. Assumptions made for the calculation of wind power density of Çanakkale were as follows:

- Air density was assumed as constant
- No turbine efficiency was considered
- Weibull model was used for fit
- No topographical parameters were considered.

The following is the general formula to calculate available wind energy per unit area [67].

$$WPD = \frac{1}{2} \rho V^3 \quad (4.11)$$

where, ρ is the air density (assumed as 1.225 kg/m^3 under standard conditions) and v is the wind speed in m/s. To account for the variability, V^3 was calculated by using the fitted Weibull parameters with the following formula [70].

$$V^3 = c^3 \Gamma \left(1 + \frac{1}{k} \right) \quad (4.12)$$

The annual wind power density was calculated as 2342 kWh/m^2 for Çanakkale. In Türkiye Wind Energy Potential Atlas, average wind power density for Çanakkale was given as 305.25 MW/m^2 [71], which gives an annual density of 2673 kWh/m^2 . The difference of 12% was acceptable since in the model a 4-year period was used to fit the data, rather than the hourly values of wind speeds. These wind power density results show that Çanakkale is a fair site in terms of resource potential [72].

4.4. Wind Turbine Selection and Energy Output Modeling

Selection of a suitable wind turbine model is critical to estimate annual energy outputs under site specific conditions. A comparative assessment of three different

commercially available turbines was conducted based on the technical specifications and compatibility with the wind profiles.

4.4.1. Overview of Candidate Wind Turbines

Wind turbine selection was one of the critical steps in modeling the wind-to-hydrogen system. The turbine needed to be appropriate for site-specific conditions and capable of maximizing annual energy production. In this study, three wind turbines that are commercially used in Türkiye were compared for integration into the wind-to-hydrogen model. The GE 4.3-158 turbine had the largest swept area due to its rotor diameter and was expected to perform well under moderate wind conditions.

In the following sections, a detailed evaluation was carried out to select the optimal turbine for the Çanakkale case study, which was then used for national-scale modeling. Both the Levelized Cost of Electricity (LCOE) and Levelized Cost of Hydrogen (LCOH) were calculated to identify the most economically viable option. Table 7 provides an overview of the technical specifications of the three wind turbines considered in the study, including their classification based on International Electrotechnical Commission (IEC) standards.

Table 4.5: Comparison of commercially available turbines.

Parameter	Turbine 1	Turbine 2	Turbine 3
Manufacturer	Nordex	GE	GE
Model	N131/3600	5.3-158	GE 2.75/103
Rated power (kW)	3600	5300	2750
Rotor diameter (m)	131	158	103
Hub height (m)	Up to 134 m	Up to 160 m	Up to 123.5 m
Cut-in wind speed (m/s)	3	3	3
Cut-out wind speed (m/s)	25	22	25
Rated wind speed (m/s)	12	13	13.5
Classification	IEC II	IEC S	IEC IIIa

4.4.2. Technoeconomic Evaluation of Candidate Turbines

This section provides a comprehensive technoeconomic evaluation for the candidate turbines. The objective was to identify the turbine that offered the best balance between energy production and cost per unit of electricity at the case site. The evaluation was

based on two key indicators: Annual Energy Production (AEP) and LCOE. These metrics enabled an evidence-based turbine selection prior to hydrogen production system modeling.

All turbines were assumed to operate over a 25-year project lifetime with a discount rate of 8%. CAPEX included the turbine, foundation, electrical infrastructure, and installation costs, which were estimated from market surveys specific to each turbine. Operation and maintenance (O&M) costs were expressed per megawatt-hour of electricity generated, reflecting typical service contracts and corrective maintenance expenses [73].

AEP represents the total energy output of a wind turbine over the course of one year. It is determined by the turbine power curve and the wind speed distribution at the hub height. For the case site, monthly Weibull distributions were fitted to ERA5 wind data at 100 meters, and bias correction was applied using regional averages obtained from the Türkiye Wind Energy Potential Atlas.

The AEP was calculated using a bin-based integration approach. The wind speed range was discretized into 0.5 m/s intervals, starting from 0 m/s up to the turbine's cut-out speed. For each bin, the probability density was computed using the two-parameter Weibull probability density function:

$$f(V) = \left(\frac{k}{c}\right) \frac{V^{k-1}}{c} \exp\left(-\left(\frac{V}{c}\right)^k\right) \quad (4.13)$$

where V is the center wind speed of the bin.

Weibull parameter k and c were calculated earlier for the case site. The energy output for each wind speed bin was determined by multiplying the Weibull probability density at the center wind speed of the bin by the turbine's corresponding power output and the number of hours per year. Each turbine was assumed to operate 95% of the time, accounting for routine maintenance and downtime requirements [74]. The total annual energy production was then calculated by summing the energy contributions from all wind speed bins.

Figure 4.3 represents the manufacturer power curves for each selected turbine and the wind speed distribution comparison. It represents the electrical output of each turbine

for the wind speed at hub height, and it was used for AEP calculations. As seen, all three turbines start generating electricity at their cut in speed, 3 m/s and reach the rated output at their rated wind speeds around 12 m/s. The Weibull distribution confirms that most wind speed for the case site falls between 5-9 m/s range and this favors turbines with broad partial-load operation. It was expected for GE-5.3 and Nordex models to generate more energy which were confirmed through AEP and LCOE modeling.

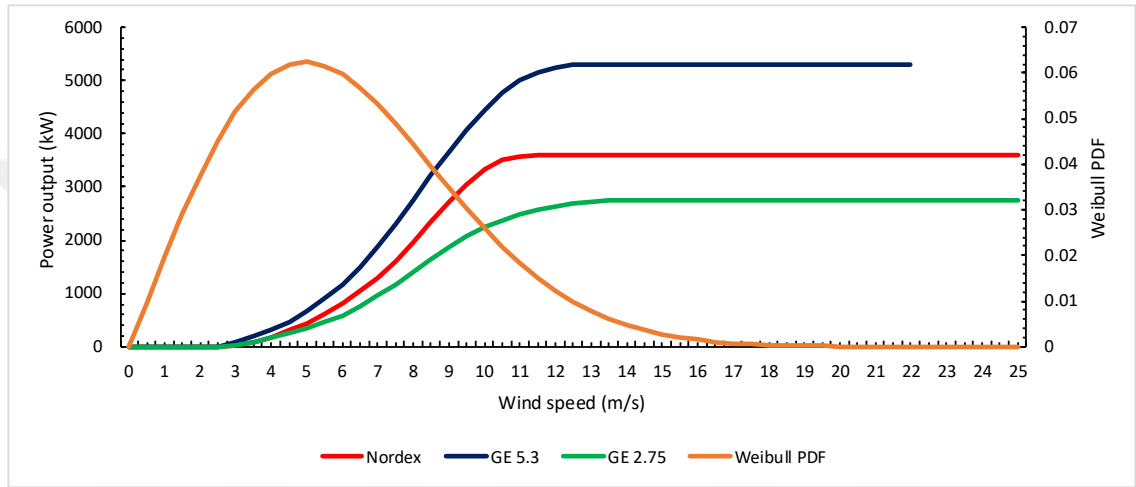


Figure 4.3: Comparison of power curves and wind speed distribution.

Figure 4.4 shows the distribution of energy output per wind speed bin for candidate turbines. As seen in the figure, energy production was the highest between wind speeds 8 to 11 m/s. The GE 5.3 model yielded the highest output due to its larger rotor diameter and rated capacity as expected.

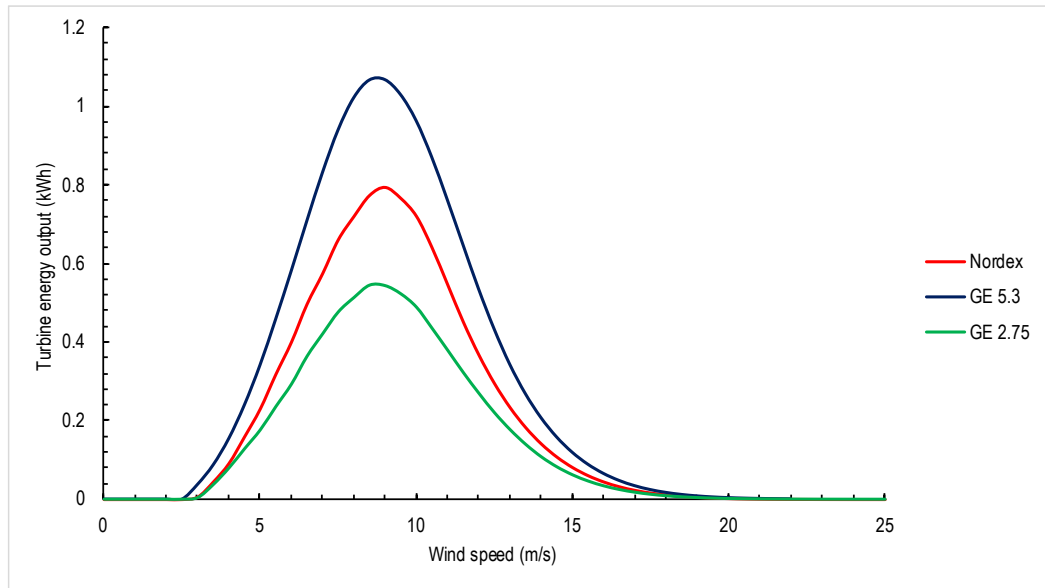


Figure 4.4: Energy output per wind speed bin for candidate turbines.

Figure 4.5 illustrates the cumulative energy production of three candidate turbines as a function of the wind speed of case site. This plot provides insight into how quickly each turbine achieved its total annual energy output under the site's wind conditions, which were modeled using the Weibull distribution. The GE 5.3 turbine demonstrated the steepest cumulative curve and reached near-saturation at approximately 13 m/s, indicating that the majority of its energy production occurred within the site's most frequent wind speed range. In contrast, the GE 2.75 model showed a slower rate of energy accumulation. Annually, the Nordex 3.6 turbine produced 10.016 GWh, the GE 5.3 turbine generated 14.190 GWh, and the GE 2.75 model yielded 7.194 GWh. These results were consistent with the earlier power curve and bin-wise output analyses, reinforcing the suitability of the GE 5.3 turbine for the case site.

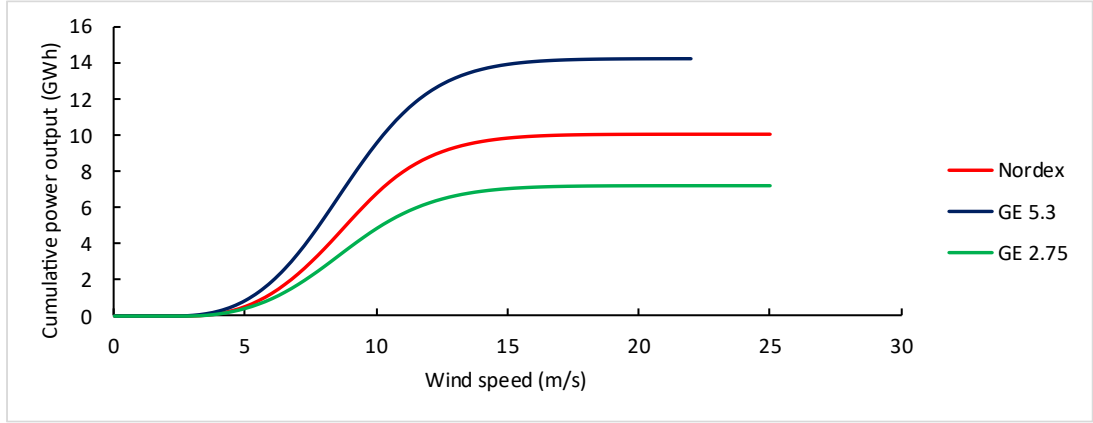


Figure 4.5: Cumulative energy output comparison of candidate turbines.

After the AEP calculations were completed, LCOE calculations were conducted to perform the economic evaluation of the candidate turbines. The LCOE served as a key indicator for comparing the cost-effectiveness of the turbines in delivering energy over their operational lifetimes. LCOE accounted for both capital investment and O&M costs, making it suitable for a direct comparison between turbines, independent of their installed capacity.

The LCOE was calculated using the standard formula [75]:

$$LCOE = \frac{CRF * CAPEX + OPEX}{AEP} \quad (4.14)$$

where LCOE is the levelized cost of electricity, CRF is the capital recovery factor, and OPEX is the operational expenses.

Total investment cost was calculated by using the CAPEX estimation from IRENA reports [73]. It was reported by IRENA that the global average selling price of wind turbines has declined significantly over the past decades reaching nearly 700-1000 USD/kW in recent years. Prices vary depending on the turbine class, rotor diameter and regional market dynamics as well as with the project size. European and American turbine manufacturers have stable prices around 900-1100 USD/kW for turbines with high capacities and Chinese turbines are priced lower. The assumed CAPEX, 1050 €/kW for each candidate turbine, was consistent with the current benchmarks. This approach reinforced the robustness of the LCOE estimation presented in economical investment of the candidate turbines.

CRF, capital recovery factor, was calculated by the following formula [75]:

$$CRF = \frac{i * (1 + i)^n}{(1 + i)^n - 1} \quad (4.15)$$

where i is the interest rate, assumed as 8% [53,76], and n is the project lifetime assumed as 25 years [53].

In Table 4.6, modelled AEP values and cost assumptions can be seen with the resulting LCOE values.

Table 4.6: LCOE comparison of candidate turbines.

Turbine	AEP (GWh/year)	Investment (€)	O&M (€)	LCOE (€/kWh)
GE 5.3-158	14.19	521322	496667	0.071
Nordex N131/3600	10.02	354105	350563	0.070
GE 2.75/103	7.19	270497	251803	0.072

According to IRENA's global cost assessment report (2023), the weighted average LCOE for onshore wind in the Eurasia region is approximately 0.091 USD/kWh (91 USD/MWh), with a range between 43 and 112 USD/MWh [75]. The LCOE calculated for the case site was positioned near the middle of this distribution and was consistent with the moderate wind speed conditions observed, as well as the conservative assumptions adopted in the turbine modeling. Although the Nordex N131/3600 turbine yielded the lowest LCOE, the GE 5.3-158 was also considered for the hydrogen production modeling due to its higher energy yield and better suitability for system integration. Its greater AEP was a critical factor, as the volume and consistency of delivered energy directly influence electrolyzer efficiency and capacity factor. This, in turn, is expected to result in greater hydrogen output and potentially lower LCOH. Therefore, LCOE alone was not considered sufficient for turbine selection. A broader evaluation of system-wide technoeconomic performance, including land use optimization, was necessary to support the final choice..

4.4.3. Turbine Sitting and Land Use

Placement of turbines plays a crucial role in wind farm design as it directly affects both technical performance and feasibility. Turbine sitting must consider aerodynamic effects, terrain constraints, environmental limitations and land availability. Site suitability therefore should include geological issues, environmental issues, safety issues, public acceptance, interconnection issues, topographical issues, and economic issues.

Due to the placement of the wind turbines, there will be an energy loss which is named as array loss. This is mainly the function of wind turbine spacing, number of turbines, turbulence intensity, frequency distribution and operating characteristics [67].

While wake effects and array losses can impact the performance of the wind farm, in this study these were assumed to be captured within the capacity factors of the selected sites. Therefore, no additional wake modeling was done in this study. Mainly the data from Türkiye Wind Energy Potential Atlas was used to calculate the total potential of the selected site. In Türkiye Wind Energy Potential Atlas, areas that are not suitable for wind farms are marked as gray and they are the areas which are:

- Areas with an elevation of 1500 meters and a slope of more than 20%
- Villages and neighborhoods
- Railways, highways, airports and ports
- Rivers, lakes, forest areas, environmental protection areas
- Power plants
- Safety zones.

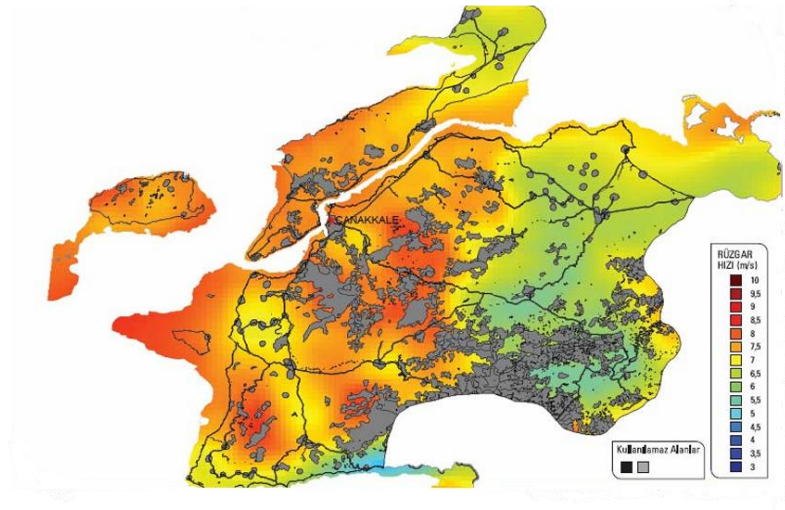


Figure 4.6: Usable and nonusable land area for Çanakkale

The calculations in Türkiye Wind Energy Potential Atlas for Türkiye's wind energy potential includes parameters related to turbine sitting as well. Therefore, the assumptions from Türkiye Wind Energy Potential Atlas was used to calculate total turbine number and hydrogen potential. Again, according to Türkiye Wind Energy Potential Atlas, total area for Çanakkale that is suitable for wind turbines was given as 2602.51 km² [58]. With the density of 5.3 MW/km², total capacity can be estimated as 13793.3 MW.

Turbine deployment over the technically available land area in Çanakkale was estimated by assuming a maximum deployment density of 5.3 MW/km² for both turbine models. The Nordex model allowed for the installation of a greater number of turbines due to its smaller rotor diameter and lower rated power; however, the land area allocated per turbine was reduced as a result. Table 9 presents the outcomes of the land use assumptions applied in this analysis.

Table 4.7: Sitting and land use assumptions for candidate turbines.

Parameter	GE 5.3-158	Nordex N131/3600
Rater power (MW)	5.3	3.6
Rotor diameter (m)	158	131
Land area per turbine (km ²)	1.00	0.68
Maximum turbine density (MW/km ²)	5.3	5.3
Available land (km ²)	2602.51	2602.51
Total no of turbines	2602	3831

Although the available land data was taken directly from Türkiye Wind Energy Potential Atlas, it should be acknowledged that project-specific limitations may reduce the actual deployable capacity.

4.5. Hydrogen Production Modeling for Case Site

Hydrogen production modeling based on the energy output from the wind turbines was presented in this section for the case site. The analysis included electrolyzer selection, system efficiency assumptions, and the alignment of wind energy supply with electrolyzer operation. Both standalone and integrated system configurations were assessed to enable an economic comparison and to analyze overall system performance..

4.5.1. Electrolyzer Technology Selection

Green hydrogen production involves two main components: a renewable energy source and a water electrolyzer. During electrolysis, water is decomposed into hydrogen and oxygen using electrical energy supplied to the electrolyzer. The most commonly used electrolyzer technologies for green hydrogen production include proton exchange membrane (PEM), alkaline water electrolyzer (AWE), anion exchange membrane (AEM), and solid oxide electrolyzer (SOE) [77]. An overview of the comparison of different electrolyzer types was provided in Table 4.8.

Table 4.8: Electrolyzer comparison [78].

Property	SOE	AEM	AWE	PEM
Technology maturity	Early commercial	Commercially used	Commercially used	Commercially used
Carrier	O ²⁻	OH ⁻	OH ⁻	H ⁺
Electrolyte	Solid ceramic	Solid polymer	Aqueous solution	Solid polymer
Working fluid	Steam	Distilled water or low concentration solution	High concentration solution	Distilled water
Anode	LSMYSZ, CatO ₃	Ni alloys	Ni	Pt; IR; Ru
Cathode	Nicermets	N,, Ni-Fe, Ni-Fe ₂ O ₄	Ni alloys	Pt;Pt=C
Operating temperature (°C)	650-1000	50-70	65-100	70-90
Operating pressure (bar)	<30	Up to 35	2-10	15-30
Efficiency	90	-	62-82	67-84
Higher Heating Value (HHV)				
Cell voltage	0.95-1.3	1.85	1.8-2.4	1.8-2.4
Current density (A/cm ²)	0.3-1	0.1-0.5	0.2-0.4	0.6-2
Startup duration (min)	>60	-	15	<15
Stack lifetime (h)	>40000	>10000	<90000	<40000
Energy consumption (kWh/Nm ³)	2.5-3.5	4.8	4.5-7	4.5-7.5
Estimated cost by 2050 (\$/kW)	200	-	600	750

As SOE type is in early commercial phase, advantages and disadvantages of the AEM, PEM and AWE were further analyzed. Table 4.9 outlines the advantages and disadvantages of these technologies that can be coupled wind renewable energy sources.

Table 4.9: Advantages and disadvantages of electrolyzer technologies [77].

Technology	PEM	AEM	AWE
Advantages	Good partial load range Compact system design High gas purity Rapid system response High current density and voltage efficiency	High durability Low cost Higher charge density	Well-established technology Cheap and effective Long term durability
Disadvantages	High CAPEX Acidic environment Low durability Nobel metal catalyst Higher discharge pressure	Chemical and mechanical stability problems Low current density Low current efficiency Low production yield	Low current density Low gas purity Low load range for partial loads

Although PEM electrolyzers are costly, with their good partial load range advantage, high cell efficiency and fast system dynamics they are appealing for renewable energy cases [79]. Hence, PEM electrolyzer was considered in this study for hydrogen production.

4.5.2. Electrolyzer Efficiency and Energy Requirements

Electrolyzer efficiency is defined as the ratio of the energy content of the produced hydrogen to the electrical energy input required for its production. According to IRENA's 2020 system-level benchmarks, PEM electrolyzers require between 50 and 83 kWh of electricity per kilogram of hydrogen, which corresponds to system efficiencies between 40% and 66% based on the Lower Heating Value (LHV). For future projections, IRENA estimates that PEM system energy consumption could decrease to below 45 kWh/kg H₂ by 2050, corresponding to an LHV-based efficiency of approximately 74% [28]. In this model, a system-level efficiency of 65% was used for PEM electrolysis to reflect the performance of current commercial systems. Electrolyzer efficiency was assumed to remain constant across all load levels to

simplify integration with the wind generation profile and to ensure consistent comparison across different turbine configurations.

4.5.3. Hydrogen Yield from Wind-Powered System

The aim of this section was to present the methodology and results of calculating hydrogen output from the wind-electricity generation that was modelled in previous sections.

Hydrogen yield was estimated using the following equation:

$$\text{Hydrogen yield (kg)} = \frac{E_{usable}}{E_{required}} \quad (4.16)$$

where E_{usable} is the electricity produced by the turbine system (kWh/year), and $E_{required}$ is the energy required to produce 1 kg of hydrogen (kWh/kg).

The system wide PEM electrolyzer efficiency was assumed as 65% in LHV basis which corresponds to an energy requirement of:

$$E_{required} = \frac{33.33 \text{ kWh/kg}}{0.65} = 51.28 \text{ kWh/kg} \quad (4.17)$$

Hydrogen output was computed for both candidate turbines based on their AEP in a one turbine–one electrolyzer configuration. This one-to-one setup assumed that each turbine was directly coupled to a PEM electrolyzer, with energy input calculated using the Weibull-distributed wind speed profile at the site. Hydrogen output was then determined by dividing the AEP by the energy requirement for hydrogen production, based on the assumed system efficiency. This simplified model did not include energy storage or buffering, allowing for a direct comparison of turbine and electrolyzer performance. Nevertheless, the inherent variability of wind was implicitly captured through the bin-based energy modeling approach. The model excluded curtailment resulting from turbine-electrolyzer mismatch, part-load efficiency variations, dynamic ramping behavior, and electrolyzer off-states. These dynamics were planned to be modeled separately at the monthly level to reflect operational realities more accurately.

For each turbine-electrolyzer pair, the Levelized Cost of Hydrogen (LCOH) was computed using the standard discounted cash flow formula [17].

$$LCOH = \frac{I * CRF + C_{stack} + C_{OPEX} + C_{electricity}}{Annual\ Hydrogen\ Output} \quad (4.18)$$

where I is the total installed system capacity, CRF is the capital recovery factor, C_{stack} is the annualized cost of stack replacements, C_{OPEX} is the annual fixed operation and maintenance cost, and $C_{electricity}$ is the cost of wind electricity input to the electrolyzer.

One of the critical factors influencing the LCOH calculation is the sizing of the electrolyzer. An undersized electrolyzer leads to increased energy curtailment, while an oversized system results in higher CAPEX, thereby increasing the LCOH. For the standalone systems in this study, electrolyzer capacity was determined using a technoeconomic optimization approach. Microsoft Excel's Solver tool was employed to minimize LCOH while ensuring that wind energy curtailment remained below a specified threshold. All cost assumptions and input parameters used in the LCOH calculation were summarized in Table 12.

Table 4.10: LCOH input parameters.

Parameter	Symbol Unit	Nordex	GE 5.3	Type	Reference
Electrolyzer CAPEX	€/kW	2500	2500	Assumed	[80]
Turbine AEP	GWh/year	10.016	14.190	Calculated	-
Electricity cost (LCOE)	€/kW	0.070	0.071	Calculated	-
Electrolyzer efficiency	%	65	65	Assumed	[28]
O&M Cost	% of CAPEX/year	2	2	Assumed	[52]
Stack replacement cost	% of CAPEX/year	15	15	Assumed	[52]
Stack durability	hours	80000	80000	Assumed	[52]
CRF (8%, 25 years)	-	0.094	0.094	Calculated	-

A sensitivity analysis was performed to illustrate how curtailment and LCOH were changing with the electrolyzer capacity. The curtailment was set to different percentages of AEP and again excel solver was used to find optimum electrolyzer capacity for the minimum LCOH. The resulting electrolyzer capacities and LCOH values are given in Table 4.11.

Table 4.11: Sensitivity of LCOH and electrolyzer capacity to curtailment.

Curtailment	Nordex		GE 5.3	
	Electrolyzer capacity (MW)	LCOH (€/kg H₂)	Electrolyzer capacity (MW)	LCOH (€/kg H₂)
≤ 10%	2.7	8.24	3.8	8.25
≤ 15%	2.4	7.98	3.3	7.96
≤ 20%	2.2	7.76	3.0	7.74
≤ 25%	1.9	7.55	2.6	7.54
≤ 30%	1.7	7.38	2.3	7.35
≤ 35%	1.5	7.22	2.1	7.21
≤ 40%	1.3	7.06	1.8	7.06
Max	0.5	6.37	1.6	6.18

As expected, higher curtailment thresholds allowed for smaller electrolyzer capacities, this improves equipment utilization and reduces CAPEX which leads to lower LCOH. Conversely, smaller curtailments required larger electrolyzer capacities and increased CAPEX resulting in higher LCOH values. It was also shown that for almost every curtailment restriction, GE 5.3 performed better than the Nordex turbine for the standalone system. This analysis captured the essential trade-off between system efficiency and economic performance. To visualize this trade-off the relationship between electrolyzer capacity, LCOH and curtailed energy cost of each turbine were shown in Figure 4.7 and Figure 4.8. The crossover points where both metrics were reasonably balanced, can serve as a practical design target depending on whether cost, yield or renewable energy integration is prioritized.

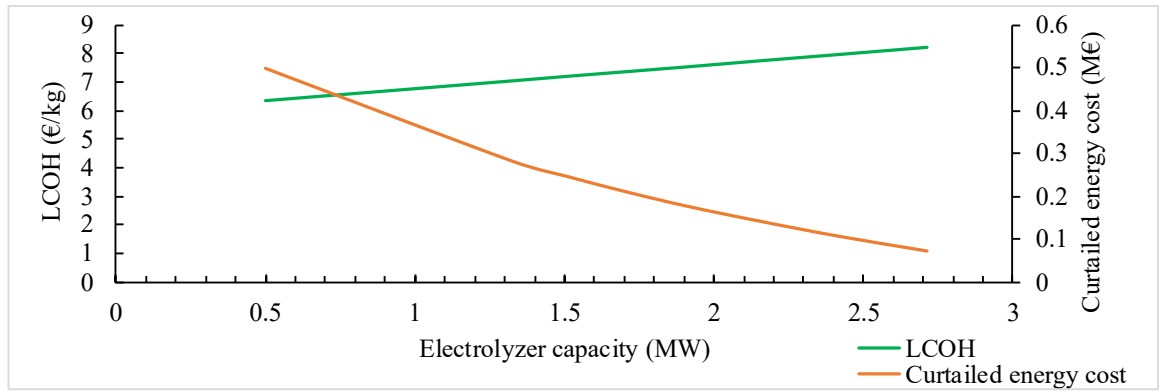


Figure 4.7: Curtailment impact on electrolyzer capacity and LCOH- Nordex.

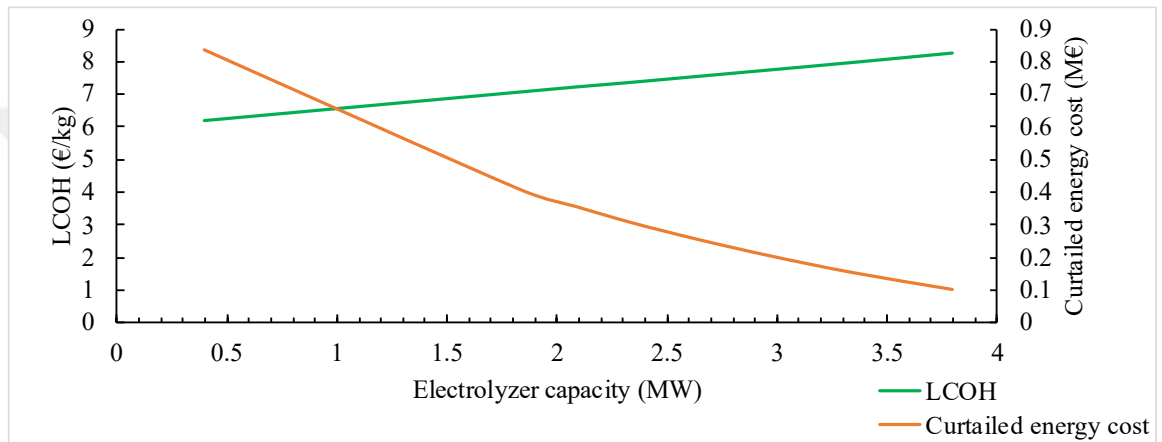


Figure 4.8: Curtailment impact on electrolyzer capacity and LCOH- GE 5.3.

Based on this comparative analysis of curtailment-constrained LCOH sensitivity, GE 5.3 turbine consistently showed better performance compared to Nordex N131/3600 turbine for the standalone operation scenario. Although the modelled LCOH remains above the current LCOH scenarios, the GE 5.3 model offered a more cost effective and scalable basis for the integrated scenarios. Therefore, this turbine configuration was selected for modeling in this study.

4.6. Seasonal Variation in Hydrogen Production

The seasonal characteristics of wind-based energy production were analyzed in this section to assess the variation in energy output for a single GE 5.3-158 turbine. Wind speed data obtained from the ERA5 reanalysis dataset were used to calculate monthly averages. These values were then corrected using the correction factor previously determined by comparing ERA5 data with the annual average from the Türkiye Wind

Energy Potential Atlas for Çanakkale. For each month, a Weibull distribution was fitted to the corrected wind speed data. The expected wind energy output was calculated by discretizing wind speeds into bins, determining each bin's contribution, and estimating the expected number of operating hours. Energy output was then calculated for each bin using the turbine's power curve.

Figure 4.9 illustrates monthly AEP, highlighting periods of high and low wind energy availability throughout the year.

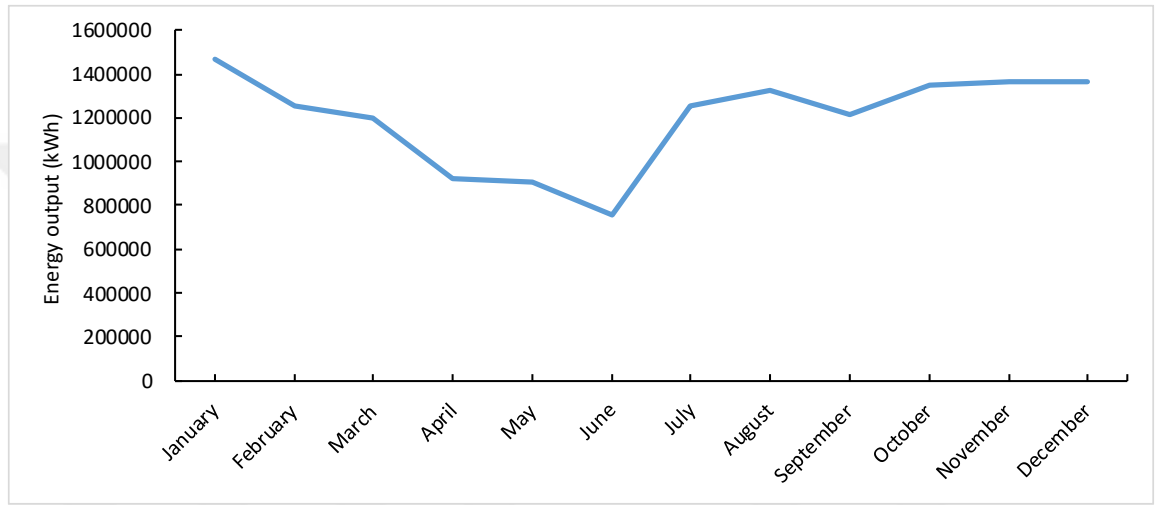


Figure 4.9: Monthly energy output from single GE 5.3-158 turbine.

The chart shows the monthly variations in energy output for the turbine. The highest output was observed in January, reaching approximately 1.467 GWh. Output declined throughout the spring, reaching a minimum in June at around 0.758 GWh. Energy generation then increased during late summer and autumn, stabilizing at approximately 1.37 GWh during the final quarter of the year.

This seasonal variability was identified as a critical factor for system design. During low-output months, downstream components such as the electrolyzer could become underutilized, while in high-output months, curtailment could increase due to excess energy. In the integrated scenario for the available land area in Çanakkale, monthly curtailments were considered to reflect these dynamics more accurately.

4.7. Integrated Wind-to-Hydrogen Model for Çanakkale

The integrated modeling of hydrogen production using the wind potential of Çanakkale was carried in this section. The main objective was to assess the system-scale performance, optimize the central electrolyzer sizing, and to determine the LCOH for the integrated system.

Based on the assumed turbine density of 5.3 MW/km², and a total available land area of 2602 km² [71], 2602 GE 5.3 turbines can be installed in Çanakkale. Each turbine has a rated capacity of 5300 kW, which yields in the total installed capacity of 13790600 kW.

The AEP from the wind farm was calculated by scaling the AEP of one turbine by the number of turbines and then the energy output from the wind farm is used to power a centralized PEM electrolyzer system. The electrolyzer was again modelled with a system efficiency of 65% and optimized for the minimum LCOH through the trade-off analysis with the curtailment of the wind farm. Table 4.12 summarizes the system configuration for the wind farm.

Table 4.12: System configuration for integrated wind farm.

Parameter	Value
Turbine model	GE 5.3-158
Number of turbines	5300 kW
Total installed wind capacity	13,790 MWh
Land area utilized	2602.51 km ²
AEP of wind farm	37.414 TWh
Electrolyzer system efficiency	65%
Electrolyzer CAPEX	2500 €/kW
System lifetime	25 years
Discount rate	8%

To capture seasonal variability, the monthly wind energy generation from the entire wind farm was calculated based on the scaled monthly AEP values. For each month, electrolyzer intake was capped by its capacity and the hydrogen output was calculated using the energy input and electrolyzer system efficiency. Where the available wind energy exceeds the electrolyzers monthly capacity, the difference was recorded as curtailment. This monthly approach enables the evaluation of the system's monthly utilization to see system performance and balancing needs. Therefore, the optimum electrolyzer sizing was crucial to find the balance between hydrogen generation and

curtailed energy. The sensitivity analysis was done by using Excel's Solver tool by varying the system curtailment by changing the electrolyzer capacity to obtain the minimum LCOH. Figure 4.10 illustrates this trade-off.

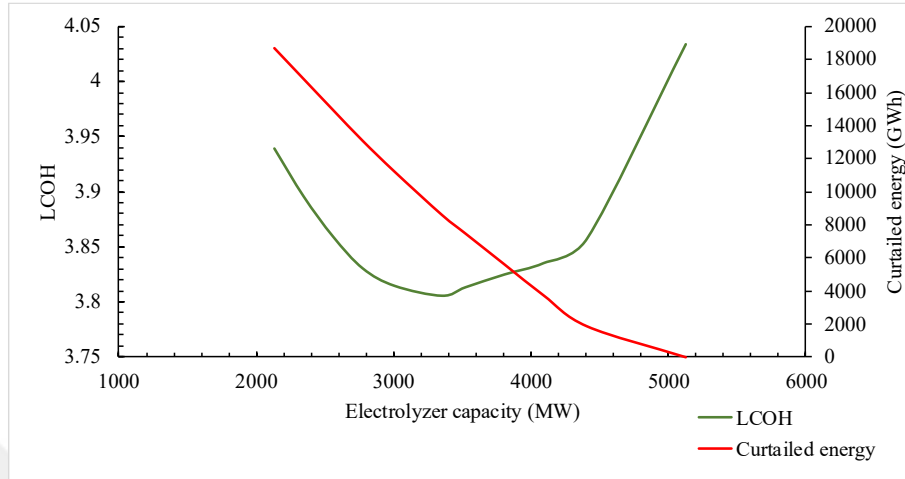


Figure 4.10: LCOH and curtailment behavior for changing electrolyzer capacity.

As seen, with the increasing electrolyzer capacity, curtailment decreases rapidly hence hydrogen production increases. The minimum LCOH was obtained as 3.8 €/kg H₂ with the electrolyzer capacity of 3357 MW. For this system the curtailment was 23% of the AEP. Higher curtailment led to a decreased hydrogen production, hence for the modeling approach, the curtailment was kept at 20% for all provinces.

These results showed that under current cost assumptions, the production of green hydrogen in Çanakkale was technically and economically feasible at the LCOH of 3.8 €/kg H₂. This value approached the target price range of 2-4 €/kg H₂ which was set by EU and international policy initiatives for 2030. While the model LCOH was still above fossil hydrogen cost, the system becomes significantly viable under expected future CAPEX declines which was introduced while scaling the model to Türkiye. Additionally, if electricity from curtailed wind were sold to grid or stored, the effective production cost can decrease further. Table 4.13 summarizes the LCOH values for hydrogen obtained from natural gas with green hydrogen targets for 2030 and 2050.

Table 4.13: LCOH values for natural gas based and renewable based hydrogen.

Source/Scenario	LCOH (€/kg H ₂)	Notes
Çanakkale model in this study	3.75	Based on 2500 €/kW electrolyzer CAPEX estimation
LCOH from natural gas [54]	0.5-1.6	IEA estimates
IRENA (2030-target, wind based) [57]	2.3-3.2	For Türkiye from global LCOH map, accounts for onshore wind supported with solar PV
IRENA (2030-target, wind based) [57]	1.4-2.3	Reflects cost reductions in renewables and electrolysis

4.8. Limitations of The Model

While the integrated model provided a realistic and data-driven foundation for the assessment, several simplifications were introduced to maintain tractability and focus. The model operated on a monthly time scale, using Weibull-fitted wind speed distributions. Although this approach effectively captured seasonal variability, it did not reflect hourly fluctuations that could influence curtailment patterns and electrolyzer utilization. The electrolyzer was modeled with a fixed system efficiency of 65%, assuming constant performance across all operating conditions. In reality, start-up dynamics, part-load behavior, and transient response would impact hydrogen yield under varying conditions. Also, the model did not incorporate energy storage or grid export systems. As a result, curtailed energy was treated as a lost resource, and the potential value of hybrid system configurations was not accounted for. Turbine siting was assumed to be uniformly feasible across all technically available land. However, actual deployment would be subject to local environmental constraints, permitting, and land-use conflicts, which could reduce the effective installation area.

Finally, cost assumptions for CAPEX and O&M were modeled as fixed inputs per unit of installed capacity. Region-specific variations in cost, supply chain challenges, and possible cost escalation due to inflation or market dynamics were not considered.

5. SCALING HYDROGEN POTENTIAL TO TÜRKİYE

Based on the model established for the case site, in this chapter the analysis was expanded to national scale. Using standardized methodology, city level wind characteristics, turbine deployment potential and hydrogen output were modelled for each city.

5.1. Introduction and Approach

As the transition to a low-carbon economy required the development of scalable and clean hydrogen strategies, wind-powered electrolysis represented a promising production route. While the single-site modeling described earlier for the Çanakkale site allowed for an in-depth technical analysis, it was not sufficient to inform policy or investment decisions at the national scale. Scaling the model across multiple regions enabled a deeper understanding of seasonal variability, land availability, and regional optimization opportunities.

5.1.1. Role of the Çanakkale Model as Reference

As a case study, the Çanakkale model was developed to serve as the foundational framework for national-scale hydrogen potential estimation. The model incorporated all major components of a wind-to-hydrogen system, including Weibull-based wind speed characterization, turbine selection based on local wind class, monthly energy yield estimation, and electrolyzer capacity matching for both annual and seasonal hydrogen production in a standalone configuration.

It was also acknowledged that regional differences in terrain, wind variability, and infrastructure access would influence system performance in other locations. These differences were partially addressed in this thesis by adjusting turbine densities and capacity factors according to city-specific conditions..

5.1.2. Overview of the Scaling Methodology

To scale Çanakkale model to the national level, windfarm-based framework was applied at the national level. Rather than modeling each turbine individually, a standard wind farm unit was used as the building block for estimating city-based hydrogen production potential. The steps were as follows:

- City Identification
- Wind Farm Deployment Estimation
- Modular Wind Farm Model
- Electrolyzer System Integration
- Regional and National Aggregation

5.2. Regional Wind Analysis

In this study, wind-based hydrogen production modeling was conducted for all cities across Türkiye's seven regions. For each city, ERA5 hourly wind data at a hub height of 100 meters was fitted to a Weibull distribution. This analysis allowed for the identification of inter-regional differences in wind regimes. Table 16 presents the average wind speeds obtained from both ERA5 and the Türkiye Wind Energy Potential Atlas. The discrepancies between the two datasets can be attributed to the coarser spatial resolution of ERA5, which cannot fully account for local terrain variations. Therefore, the data from the Türkiye Wind Energy Potential Atlas were used for bias correction. It should be noted that the ERA5 dataset covers a 4-year period, whereas the Wind Energy Potential Atlas likely reflects long-term multi-year averages. Figure 11 displays the average wind speeds for each city, while Table 16 summarizes the regional average wind speeds from both sources.

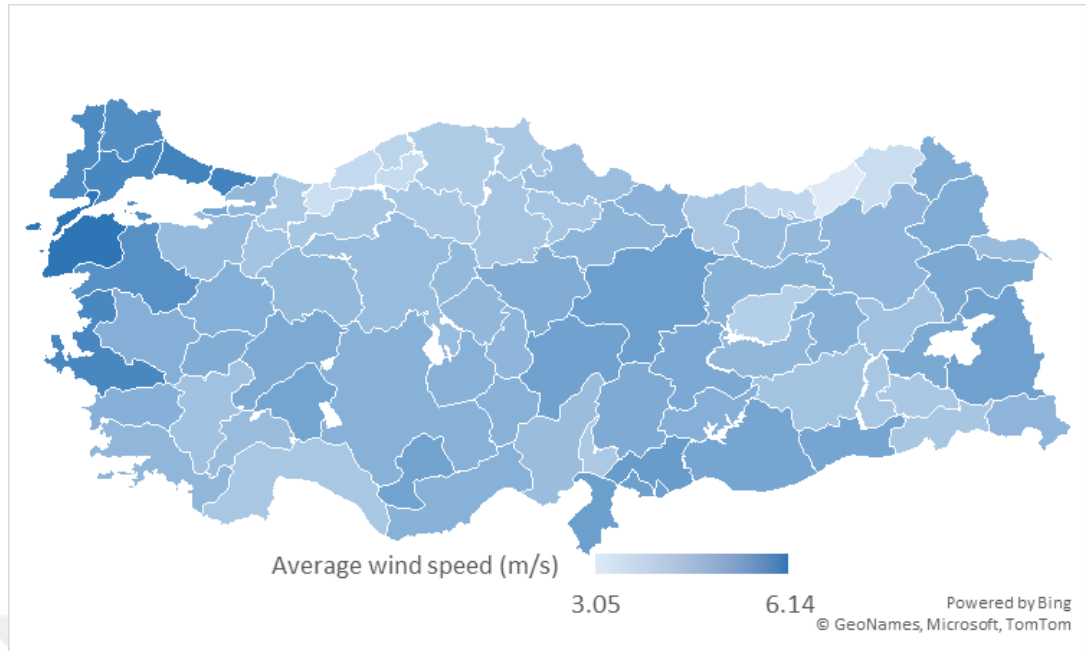


Figure 5.1: Average wind speeds.

Table 5.1: Average wind speeds for Türkiye's regions.

Region	ERA5 average wind speed (m/s)	Türkiye Wind Energy Potential Atlas average wind speed (m/s)
Aegean	3.1	4.7
Black Sea	3.2	3.9
Central Anatolia	3.3	4.5
Easter Anatolia	2.5	4.5
Marmara	4.2	5.1
Mediterranean	2.8	4.5
Southeastern Anatolia	3.1	4.5

Along with wind speeds, the Weibull scale (c) and shape (k) parameters were compared across regions. The scale parameter indicates the overall windiness of a location, while the shape parameter reflects the sharpness or peakedness of the wind speed distribution [81]. As shown in Table 17, the Marmara region exhibited the highest c value, suggesting the windiest conditions among all regions. Additionally, the k value in Marmara was also higher, indicating a more consistent wind profile, which makes the region particularly favorable for wind energy applications. Overall, the k values ranged between 1.90 and 2.04, indicating a relatively stable wind regime across Türkiye. On the other hand, c values between 4.38 and 5.72 m/s suggest a medium-level wind potential.

Table 5.2: Shape and scale parameter averages for Türkiye's regions.

Region	Shape parameter, k	Scale parameter, c (m/s)	RMSE
Aegean	1.96	5.28	0.0079
Black Sea	1.97	4.38	0.0058
Central Anatolia	1.90	5.12	0.0090
Easter Anatolia	2.03	5.10	0.0076
Marmara	2.04	5.72	0.0048
Mediterranean	2.02	5.04	0.0063
Southeastern Anatolia	2.01	5.08	0.0082

5.2.1. Estimation of Installable Wind Capacity per City

In this thesis study, the estimation of installable wind capacity for each city was carried out using the available data from the Türkiye Wind Energy Potential Atlas. This atlas provides estimates of suitable land areas for wind energy deployment, taking into account topographic, environmental, and regulatory constraints. The turbine deployment density assumption was also adopted from the same source, set at 5.3 MW/km². For each city, the available land area (in km²) was multiplied by this density value to estimate the total installable wind capacity.

Table 18 summarizes the average installable wind capacity by region. As expected, the Marmara region emerged as the highest capacity holder, with an average installable wind capacity exceeding 4546.8 MW. The Aegean region also demonstrated strong potential, with approximately 3481 MW. In contrast, Eastern and Southeastern Anatolia ranked the lowest, with average installable capacities below 320 MW, primarily due to geographical constraints, limited suitable land, and lower wind intensity.

Table 5.3: Average installable wind capacity averages for seven regions.

Region	Average installable wind capacity (MWh)
Aegean	3481.3
Black Sea	819.2
Central Anatolia	884.9
Eastern Anatolia	303.8
Marmara	4546.8
Mediterranean	1737.3
Southeastern Anatolia	313.5

5.3. Wind to Hydrogen System Architecture for Türkiye

In this section, the system architecture developed to model wind-to-hydrogen integration across Türkiye was presented. Based on regional wind resource assessments, an integrated turbine deployment approach was adopted. The electrolyzer deployment strategy and the sizing methodology used for electrolyzers were also introduced.

5.3.1. Wind Farm and Electrolyzer Deployment Strategy

Wind farm sizing was conducted based on city-level available land area for turbine deployment. Rather than assuming a uniform wind farm size across all regions, each city was modeled individually using its own deployable land potential. A consistent wind turbine model, the GE 5.3-158, was applied across all cities, as it was previously selected in the case study due to its higher energy yield per unit capacity. Turbine spacing was implicitly incorporated using an assumed deployment density of 5.3 MW/km², in alignment with national wind development guidelines.

In all city-level models, full land area utilization was assumed to simulate a high-integration scenario and to estimate the technical upper limit of wind-to-hydrogen capacity. This uniform methodology facilitates flexible, comparative technoeconomic analysis across regions while maintaining scalability.

Following wind farm modeling, a centralized electrolyzer deployment strategy was adopted. In this approach, the entire wind energy output per city was assumed to be directed into a shared PEM electrolyzer system, enabling optimized electrolyzer sizing. PEM technology was selected based on the findings from the case study, where it was identified as the most commercially mature and technically suitable option for integration with variable renewable energy sources.

5.3.2. Electrolyzer Sizing Approaches

Electrolyzer sizing played a critical role in determining the performance and cost-effectiveness of wind-to-hydrogen systems. In the national scaling phase of this study, a capacity sweep approach was applied to identify the optimal electrolyzer sizing that minimized the LCOH. This was achieved by modeling hydrogen output and associated

curtailment levels across different system sizes. The optimization was conducted using Excel's Solver tool, targeting the minimum LCOH while applying standardized cost assumptions for the PEM electrolyzer unit.

The following constraints were considered throughout this optimization process:

- Electrolyzer system efficiency was kept at 65% for all cities.
- No intermediate energy storage was assumed; all hydrogen production was modelled as instantaneous relative to wind availability.
- CAPEX and OPEX assumptions were kept constant for each city.

This methodology enabled a sensitivity analysis of the trade-off between curtailment and cost performance, accounting for the variability in regional wind resource profiles.

5.4. Regional Summaries

For each city, the model developed for case site Çanakkale was applied. GE 5.3-158 wind turbines were deployed assuming a fixed turbine density within available areas derived from national datasets. The annual energy production (AEP) was then calculated using Weibull distributions per city.

Table 5.4 shows the number of turbines deployed per region, which reflects both the available land area and the quality of the wind resource for the region. Marmara and Aegean regions are superior to other regions with 9436 and 5255 turbines deployed, respectively. These regions account for the majority of Türkiye's onshore wind energy potential for hydrogen production. On the other hand, Eastern Anatolia and Southeastern Anatolia show limited number of turbine deployment, due to insufficient suitable land area. This distribution was consistent with regional wind modeling and highlights the spatial feasibility of hydrogen production. Regions with small number of turbines deployed were less likely to achieve cost efficient hydrogen production. It also should be noted that some cities did not have enough land available to deploy the selected turbine. These cities are Bayburt, Gümüşhane, Iğdır, Kars, Rize, Sakarya, Urfa and Şırnak.

Table 5.4: Number of turbines deployed per region.

Region	No of turbines deployed
Aegean	5255
Black Sea	2782
Central Anatolia	2119
Eastern Anatolia	802
Marmara	9436
Mediterranean	2622
Southeastern Anatolia	532

As indicated in Figure 12, the Marmara region dominated total wind energy production, contributing approximately 113.1 TWh, which represented more than 45% of the nationally modeled output. This outcome aligned with the high number of turbines deployed and the region's strong wind profile. The Aegean region followed with 49.6 TWh, again reflecting a dense turbine layout and favorable wind conditions. As expected, Southeastern Anatolia and Eastern Anatolia contributed 3.94 TWh and 6.2 TWh, respectively, due to their limited deployment potential. This regional breakdown provided a clear rationale for prioritizing the Marmara and Aegean regions in future wind-to-hydrogen investment strategies.

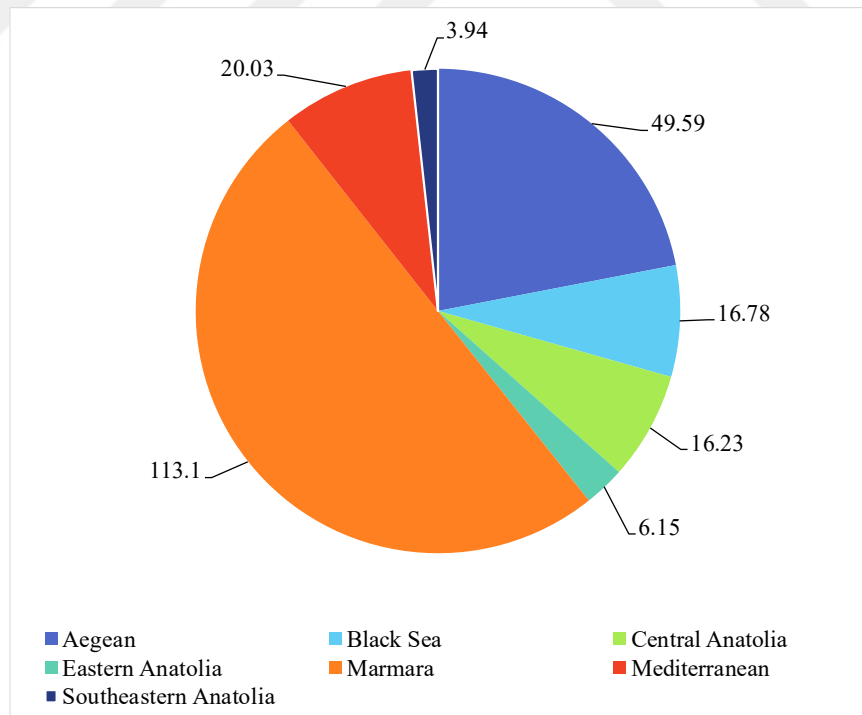
**Figure 5.2:** Regional annual energy production distribution in TWh.

Figure 5.3 illustrates the estimated annual hydrogen production by region under a full deployment scenario with zero curtailment. In alignment with wind energy production, the Marmara region led significantly, exceeding 2.1 Mt/year, while the Aegean region followed with approximately 1 Mt/year. The Mediterranean, Black Sea, and Central Anatolia regions showed moderate hydrogen outputs around 0.3–0.4 Mt/year. In contrast, Eastern Anatolia and Southeastern Anatolia combined yielded less than 0.2 Mt/year due to limited land availability and lower wind speeds. These differences in hydrogen output demonstrated how regional wind quality, land constraints, and the resulting turbine deployment directly influenced hydrogen yield.

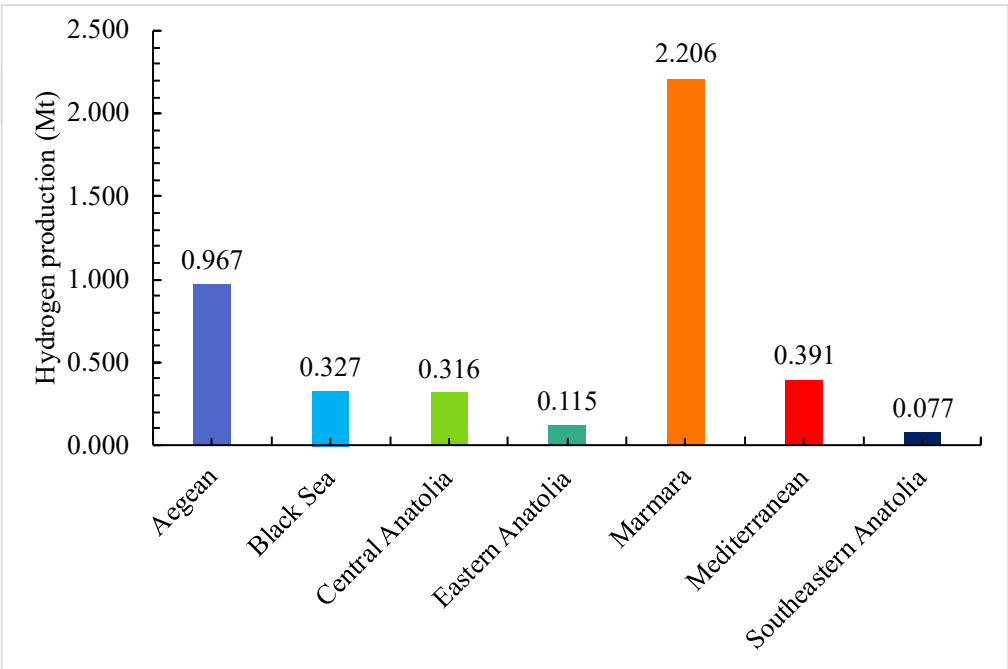


Figure 5.3: Regional hydrogen production.

5.4.1. Electrolyzer Utilization and Energy Curtailment

In Section 5.4, hydrogen production results were presented under the assumption of full utilization of wind energy—that is, with no curtailment. While this assumption was useful to identify the theoretical maximum output, it did not reflect the operational constraints under variable wind conditions. In practice, when wind energy exceeds the processing capacity of the electrolyzer, the surplus energy must be curtailed. Additionally, under a zero-curtailment assumption, the electrolyzer could become oversized due to seasonal variability in wind potential. To quantify this effect, different

curtailment ratios were analyzed for the case site, and for the national model a uniform 20% curtailment level was applied across all cities.

Figure 14 shows regional hydrogen production under this fixed 20% curtailment scenario. Compared to the baseline zero-curtailment case, hydrogen output decreased in all regions. Despite this reduction, the Marmara region still dominated national hydrogen production. This analysis underscored the importance of electrolyzer sizing strategies aimed at minimizing curtailment, as well as the potential role of flexible demand-side coupling, energy storage, or grid-integration options.

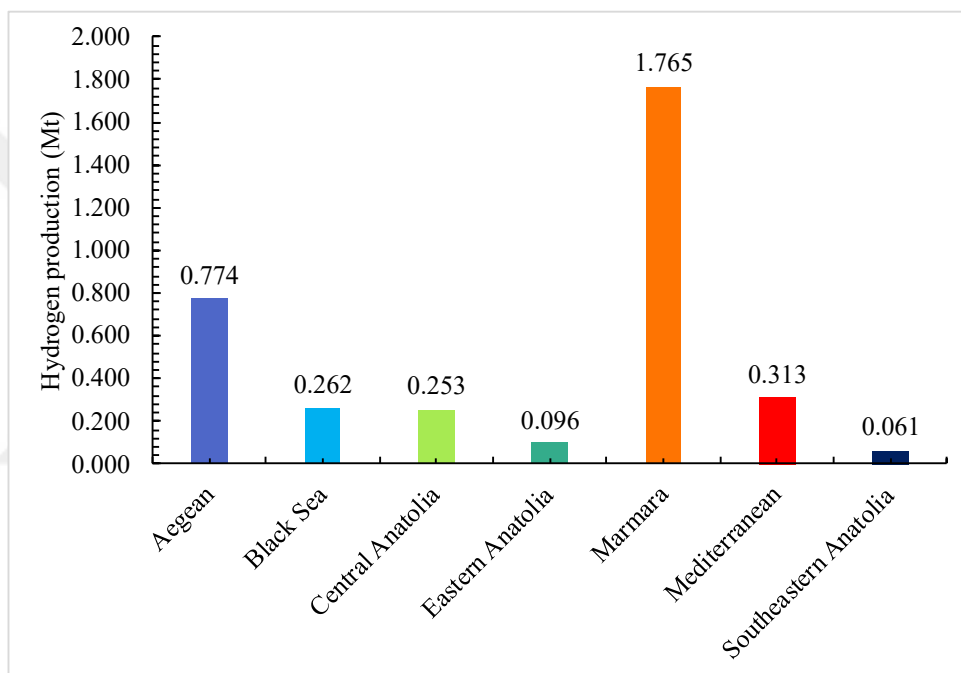


Figure 5.4: Hydrogen production under 20% curtailment.

As displayed in Figure 15, regional average electrolyzer utilization under two different curtailment scenarios was compared. In the zero-curtailment scenario, electrolyzer utilization consistently exceeded 100%, indicating that the electrolyzer capacity was over-sized relative to the total available wind energy. This suggested that the installed electrolyzer capacity surpassed the level that would be optimally needed based on the actual energy yield. In contrast, under the 20% curtailment scenario, electrolyzer utilization values ranged between 70% and 85%, reflecting a more balanced capacity sizing aligned with usable energy input. These findings emphasized the critical

importance of optimizing electrolyzer sizing to avoid overinvestment and inefficiencies due to underutilized capacity.

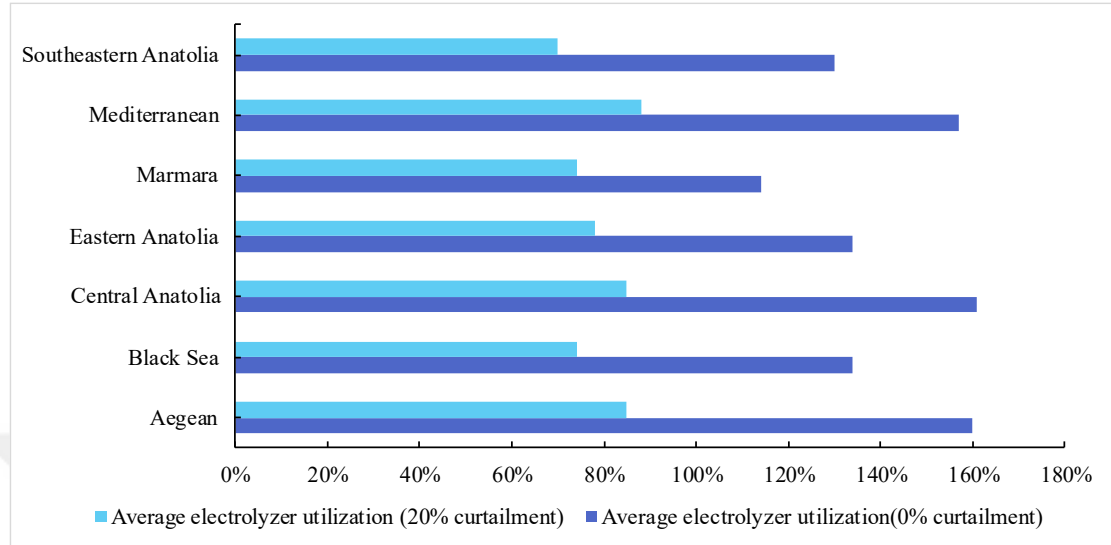


Figure 5.5: Electrolyzer utilization under 0% and 20% curtailment scenarios.

5.4.2. Seasonal Variation in Hydrogen Output

To understand the seasonal differences in hydrogen production across Türkiye's regions, a seasonal analysis of hydrogen yield was conducted. As shown in Figure 16, the Marmara region again stood out with the highest hydrogen production across all seasons. This result reflected both its high annual wind energy potential and relatively stable wind availability throughout the year. Seasonal hydrogen production values in Marmara remained within a narrow range of 0.434–0.450 Mt, indicating low seasonal sensitivity. In contrast, the Aegean region, despite its high annual production, exhibited a more pronounced seasonal decline during winter, attributed to reduced average wind speeds in the colder months. Eastern and Southeastern Anatolia showed relatively higher seasonal variation; for instance, Eastern Anatolia's hydrogen output declined from 0.028 Mt in summer and spring to 0.018 Mt in winter. This highlighted limited wind availability and consistency, which could reduce electrolyzer utilization unless supported by storage systems or hybrid strategies incorporating grid connection.

The Mediterranean region peaked during summer at 0.089 Mt, consistent with coastal wind intensification trends, whereas Central Anatolia and the Black Sea regions

demonstrated more stable seasonal output profiles. These seasonal patterns carry practical implications for system design. In regions experiencing strong seasonal drops, underutilization risks may emerge during certain months, necessitating strategies such as electrolyzer oversizing, curtailment management, or energy storage solutions to buffer supply-demand mismatches during periods of low wind generation.

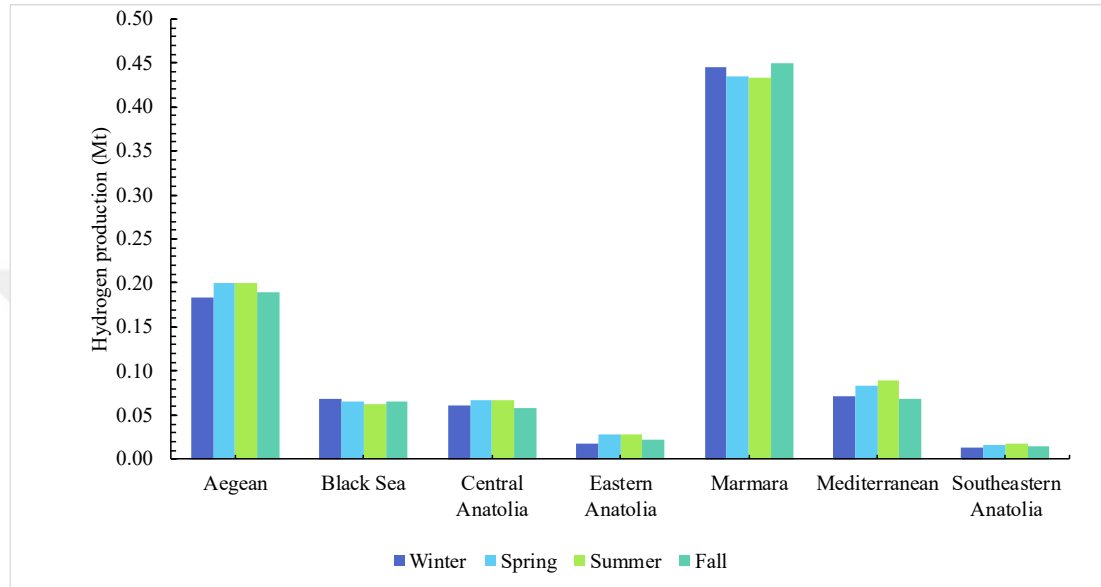


Figure 5.6: Seasonal variation in hydrogen production across seven regions.

5.5. System-Wide Integration Discussion

In this chapter, the regional modeling results were presented to evaluate the overall wind-to-hydrogen potential and operational dynamics across Türkiye. Estimates for regional capacities, as well as the potential for complementarities between regions, were introduced to inform strategic deployment and integration opportunities.

5.5.1. Total Wind-to-Hydrogen Capacity in Türkiye

Under a zero-curtailment scenario, the modeled system is capable of producing approximately 4.4 million tons (Mt) of green hydrogen annually by utilizing around 226 terawatt-hours (TWh) of onshore wind energy. However, when a more realistic 20% curtailment is applied to reflect operational limitations and system constraints, the annual hydrogen output decreases to approximately 3.5 Mt.

Under this 20% curtailment scenario, the total electrolyzer capacity required is estimated at 21.6 GW to effectively utilize the available wind energy for hydrogen production. This figure is closely aligned with Türkiye’s national hydrogen targets. According to the Türkiye Hydrogen Technologies Strategy and Roadmap, the country aims to install 2 GW of electrolyzer capacity by 2030, expand to 5 GW by 2035, and ultimately reach 70 GW by 2053 [8]. In terms of demand, Ernst & Young (2025) projects that Türkiye’s green hydrogen requirement could rise to 5.5–6 Mt by 2050 [82]. The modeled output of 3.52 Mt under the 20% curtailment scenario indicates that wind-based hydrogen can make a substantial contribution toward meeting this goal. PwC also estimates a domestic green hydrogen demand of approximately 2–2.5 Mt by 2050 [83]. The zero-curtailment scenario exceeds this forecasted demand, while the 20% curtailment case appears largely sufficient to meet it, thereby reinforcing the strategic relevance of onshore wind as a viable hydrogen production pathway for Türkiye.

Figure 18 illustrates the city-level contributions to national hydrogen output under the 20% curtailment scenario.

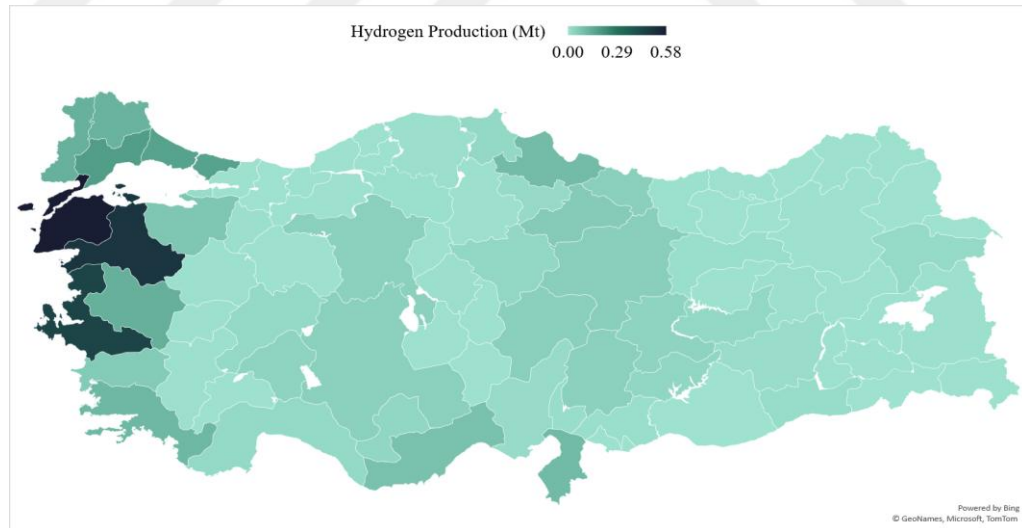


Figure 5.7: Türkiye’s green hydrogen production potential with onshore wind.

5.5.2. Regional Complementarity and Balancing Opportunities

One of the significant advantages of a geographically diverse renewable energy system is the natural complementarity that emerges among regions with differing wind

profiles. For Türkiye, the wind resource analysis conducted across the seven regions reveals distinct temporal characteristics, which can be strategically leveraged to mitigate the intermittency associated with wind power. The concept of regional complementarity has been widely discussed in the literature, particularly in the context of hybrid renewable systems that combine wind and solar resources [84,85]. For instance, Jurasz et al. (2020) investigated the solar–wind complementarity in Poland and concluded that local hybrid systems could reduce storage needs and enhance the reliability of power system operations [85]. Similarly, for Türkiye, not only the complementarity between different renewable energy sources but also city-level and regional complementarity among wind regimes should be examined to ensure stable hydrogen production throughout the year. Such integration would enable the downsizing of electrolyzer systems, addressing the inefficiencies observed in the zero-curtailment scenario.

From an infrastructure standpoint, hydrogen transport and storage capabilities are critical to unlocking regional balancing opportunities. Hydrogen Europe (2024) highlights the spatial mismatch between regions with high renewable generation potential and areas of hydrogen demand, underscoring the need for infrastructure to bridge this gap [86]. Türkiye’s national policy framework also acknowledges this challenge; the SHURA Energy Transition Centre (2018) emphasized the significance of interregional energy flows for the success of renewable energy integration [87]. These findings suggest that system-wide hydrogen planning in Türkiye should transcend isolated capacity expansion. Instead, it should be grounded in regional complementarities, inter-renewable synergies, and spatial balancing strategies. Seasonal flexibility, cross-regional hydrogen storage hubs, and demand-side coordination could all enhance the technoeconomic feasibility of green hydrogen development in the country.

Following the regional potential and system integration, an economic assessment is warranted. While earlier sections addressed the physical deployment, resource matching, and capacity estimation, the next chapter evaluates the cost-effectiveness and financial viability of nationwide hydrogen production through LCOH analysis.

6. ECONOMIC ANALYSIS FOR TÜRKİYE

The regional hydrogen production results presented in Chapter 5 provide the foundation for a national-scale assessment of economic feasibility through the Levelized Cost of Hydrogen (LCOH). As defined earlier in the Çanakkale case study, LCOH represents the average cost of hydrogen production per kilogram over the lifetime of the system, incorporating both capital expenditures (CAPEX) and operational expenditures (OPEX). For the national analysis, the same technoeconomic assumptions applied in the base model were maintained to ensure consistency. CAPEX and OPEX values for both wind energy and electrolyzer systems were derived from market-based estimates and previously referenced literature. These assumptions are summarized in Table 20, which outlines the key parameters used for the economic evaluation.

Table 6.1: Assumptions for economic analysis.

Parameter	Assumption for the model
Wind turbine CAPEX	1050 €/kW
Project lifetime	25 years
O&M cost turbine	35 €/MWh
Electrolyzer CAPEX	2500 €/kW
Stack durability	80000 h
O&M cost electrolyzer	2% of CAPEX
Electrolyzer efficiency	65%
Discount rate	8%
Curtailment	20%

Figure 19 presents the regional comparison of LCOE and LCOH derived from onshore wind-based hydrogen production. The Marmara and Aegean regions exhibit the lowest LCOH values (€3.76/kg H₂ and €3.82/kg H₂, respectively), reflecting their strong wind resource quality and high electrolyzer utilization. In contrast, Southeastern and Eastern Anatolia show higher LCOH values exceeding €4.20/kg H₂, which are driven by both elevated LCOE and reduced hydrogen yields resulting from lower wind speeds and limited turbine deployment.

Although these regional differences exist, the LCOH range remains relatively narrow, approximately €3.75/kg H₂ to €4.23/kg H₂. This indicates that cost optimization efforts must also focus on infrastructure efficiency and integration. It is important to note that

the reported LCOE and LCOH values are based on 2023 and 2024 cost assumptions and do not reflect potential future reductions that may arise through technological advancements or policy incentives. Türkiye’s strong onshore wind potential provides a solid foundation for cost-competitive green hydrogen production. The modeled values presented in this section can be considered as a baseline scenario to support future technoeconomic evaluations.

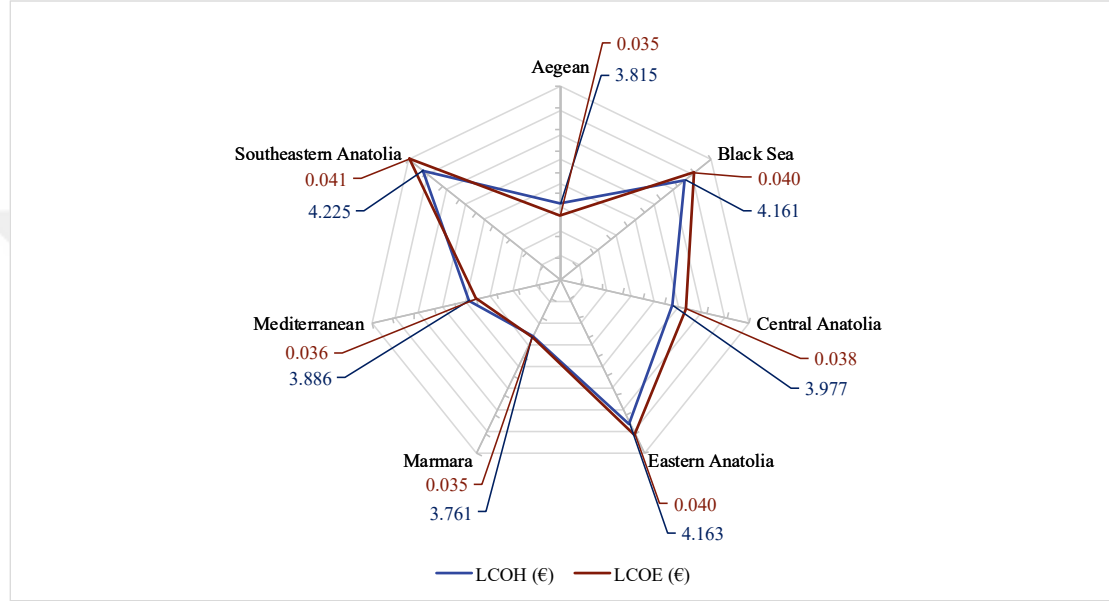


Figure 6.1: LCOE and LCOH for seven regions.

As illustrated in Figure 20, cities such as Balıkesir, Sinop, Edirne, and İzmir demonstrate the lowest LCOE and LCOH values among all seventy-three cities considered for wind-to-hydrogen system deployment. These cities combine strong wind resource availability with relatively high electrolyzer utilization, making them promising candidates for early-phase project implementation. The convergence of low LCOE and LCOH values in several coastal and near-coastal cities suggests that western and northern Türkiye could form a cost-competitive hydrogen production cluster. These findings highlight the significance of site-specific modeling to guide investment prioritization, as both regional and city-level variations can substantially impact system performance and financial feasibility.

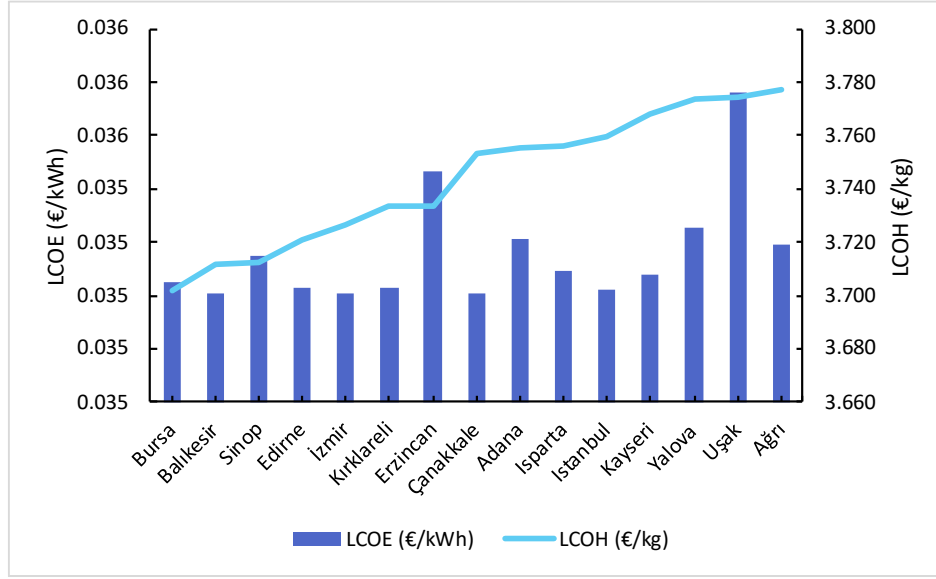


Figure 6.2: LCOE and LCOH values for high performing cities.

6.1. Sensitivity Analysis of Key Economic Parameters

The future economic competitiveness of green hydrogen production in Türkiye was evaluated through a sensitivity analysis targeting two key milestone years, 2035 and 2050. These projections reflect anticipated advancements in technology and consider reductions in capital expenditure and operational expenditure for both wind turbines and electrolyzer systems. Additionally, improvements in electrolyzer efficiency are incorporated to assess their impact on the overall levelized cost of hydrogen in future scenarios. The projections for 2035 and 2050 are given in Table 6.2.

Table 6.2: Projections for 2035 and 2050.

Parameter	2035 Scenario	2050 Scenario
CAPEX (Wind turbine) [88]	15% reduction	40% reduction
OPEX (Wind turbine) [88]	14% reduction	40% reduction
CAPEX (Electrolyzer) [52]	30% reduction	55% reduction
Electrolyzer efficiency [28]	70%	75%

The results indicated that even under conservative assumptions regarding cost reductions and energy curtailment, the levelized cost of hydrogen (LCOH) is projected to decline significantly. On average, the LCOH decreases from approximately €3.70 per kilogram in the base year to a range of €2.69 to €2.73 per kilogram by 2035. By 2050, with further technological advancements and efficiency improvements, the

LCOH is expected to fall to between €1.67 and €1.71 per kilogram for the highest-performing cities. These cities include Bursa, Balıkesir, Sinop, Edirne, İzmir, Kırklareli, Erzincan, Çanakkale, Isparta, Adana, Istanbul, Kayseri, Yalova, Ağrı, and Uşak.

These trends suggest that Türkiye could achieve globally competitive LCOH values below €2 per kilogram H₂ by 2050, provided that supportive deployment strategies and projected cost reduction pathways are realized. Among the influencing factors, the CAPEX of electrolyzers emerged as the most significant driver of LCOH reduction. Additionally, improvements in electrolyzer efficiency contribute meaningfully to lowering hydrogen production costs.

This analysis underscores the critical role of sustained technological advancement in driving down costs and enhancing system performance. Furthermore, it highlights the strategic importance of prioritizing early deployments in regions with favorable LCOE profiles. Such early actions can accelerate local capacity building and infrastructure readiness, which are essential for long-term success in the hydrogen economy.

7. DISCUSSION

The integrated assessment conducted in this study highlights the significant potential of Türkiye's onshore wind resources for green hydrogen production, with the Marmara and Aegean regions identified as the most favorable due to their high annual energy output and relatively low levelized cost of hydrogen (LCOH). Technical modeling demonstrated that deploying modern, high-capacity wind turbines across suitable land areas could generate more than 225 million megawatt-hours (MWh) of electricity annually. This corresponds to approximately 4.4 million tons (Mt) of green hydrogen under a zero-curtailment scenario, although actual production would be lower under more realistic operational constraints involving curtailed output.

LCOH values for 2024 under the zero-curtailment scenario ranged between €3.7/kg H₂ and €6.1/kg H₂, depending on regional differences in wind profiles, electrolyzer utilization, and hydrogen yield. Cities such as Bursa, Balıkesir, Çanakkale, and Tekirdağ exhibited the lowest LCOH values due to favorable wind conditions and extensive available land areas. In contrast, Southeastern and Eastern Anatolia presented more limited feasibility owing to both lower wind capacity and reduced deployment area.

While environmental impacts were not quantified in detail, the transition from grey hydrogen or fossil fuels to green hydrogen offers substantial emissions reduction potential. According to Hauglustaine (2024), grey hydrogen production emits approximately 10 kilograms (kg) of CO₂ per kg of hydrogen, compared to only 1 kg CO₂ per kg of hydrogen for green hydrogen [91]. This suggests that, if the modeled production capacity were fully realized, Türkiye could achieve annual carbon dioxide savings of up to 38 Mt, positioning green hydrogen as a pivotal strategy in the country's decarbonization efforts.

7.1. Policy Reflections and Implementation Pathways

Realizing the identified technical and economic potential requires the implementation of well-designed strategic policy frameworks. Türkiye's National Hydrogen Strategy provides a foundational roadmap, targeting 5 gigawatts (GW) of electrolyzer capacity by 2035 and scaling up to 70 GW by 2050. The findings of this study are closely

aligned with these national objectives, offering data-driven support for future planning and investment.

To enable effective deployment, key policy instruments should include renewable energy auctions tailored for green hydrogen projects, guaranteed offtake mechanisms to ensure market stability, and dedicated investments in grid and hydrogen infrastructure. Additionally, project prioritization should focus on maximizing wind–hydrogen integration in regions with high capacity factors, while carefully considering land availability, environmental sensitivities, and water resource constraints to ensure sustainable development.

7.2. Benchmarking Against Case Studies

Compared to global averages, Türkiye’s estimated Levelized Cost of Hydrogen (LCOH) lies within the mid-range of internationally benchmarked values. According to the International Energy Agency (IEA, 2020), the projected target range for electrolysis-based hydrogen production using low-carbon electricity by 2050 is between 1.3 and 3.3 USD/kg H₂[89]. This positions Türkiye competitively, particularly in the Marmara and Aegean regions where favorable wind conditions and proximity to infrastructure and potential export markets enhance feasibility. However, Türkiye currently lacks large-scale domestic electrolyzer manufacturing capacity, in contrast to some leading countries. Strategic partnerships with the European Union or the Middle East and North Africa (MENA) region could enable Türkiye to position itself as a regional hub for green hydrogen supply.

Several national-level studies offer valuable context for benchmarking. Karayel et al. (2023) estimated Türkiye’s onshore wind-based hydrogen potential at 233 million tons by relying on annual average wind speeds and theoretical land availability. While their estimate provides a theoretical upper bound, it lacks the spatial and seasonal resolution applied in this study. Balcı and Erbay (2025) focused on offshore wind-based hydrogen production, reporting LCOH values between €4.14 and €5.85/kg H₂. However, their site-specific and offshore-oriented scope limits broader applicability. Guven and Kayalica (2025) conducted a national-level life cycle assessment across 120 grid zones, providing valuable environmental and economic insights.

Nevertheless, their model does not incorporate seasonal wind variation or curtailment effects and reports a wide LCOH range of \$2.25 to \$7.01/kg H₂.

7.3. Opportunities, Risks and Trade-offs

Opportunities include leveraging wind-rich regions for industrial decarbonization to enable green fertilizer and steel production and creating export corridors via ports like İzmir. There are also increased job opportunities and innovation prospects linked to electrolyzer deployment and system integration.

Risks involve intermittency management, land use competition and high upfront CAPEX. Trade-offs must be balanced between centralized versus distributed systems, storage versus curtailment and export versus domestic use.

7.4. Future Research Directions

This study provides a detailed technoeconomic feasibility analysis; however, several areas require further exploration to support comprehensive decision-making. Future research should incorporate more in-depth environmental life cycle assessments, infrastructure optimization strategies, and localized site-specific modeling. Key areas for future work include the evaluation of network impacts associated with large-scale deployment coupled with storage solutions, assessment of water availability and utilization, integration of multi-sectoral hydrogen demand, development of dynamic policy simulations including carbon pricing mechanisms, detailed payback period assessments, and the investigation of offshore wind potential, hybrid renewable systems, and alternative electrolyzer technologies.

8. CONCLUSION AND RECOMMENDATIONS

This study presents a comprehensive techno economic feasibility analysis of hydrogen production from onshore wind resources in Türkiye.

ERA-5 based modeling identified Marmara and Aegean regions as the most promising regions in terms of average wind speed and installable capacity. City-level wind distribution fitting showed that scale parameter ranged between 3.4-6.9 m/s with highest values in Marmara region.

Using a standard system layout, annual hydrogen production was calculated for 73 provinces where for 8 the land area was not enough to deploy the selected turbine. Under all scenarios, Marmara and Aegean regions yielded the highest outputs while Eastern and Southeastern Anatolia showed the lowest outputs.

Oversizing electrolyzers in the base scenario led to inefficiencies for electrolyzer utilization. A 20% curtailment scenario strategically improved utilization but reduced hydrogen yield.

Monthly modeling revealed seasonal variability. This variation shows the importance of flexible infrastructure and complementarity scenarios.

The average LCOH across all provinces were calculated based on current, 2035 and 2050 assumptions of CAPEX and OPEX. Cities such as Çanakkale, Balıkesir, Kırklareli and İzmir showed the most competitive LCOH values driven by suitable wind profiles and vast availability of land.

Based on the study's findings, the following can be recommended for policymakers and investors:

First, national hydrogen strategies should prioritize regions like Marmara and Aegean for initial deployment due to their superior wind resource and available land area.

Second, oversizing issues could be addressed through modular electrolyzer setups that scale with seasonality and grid flexibility.

Third, seasonal output variation and curtailment risks can be mitigated by integrating storage systems and offtake strategies.

Lastly, while current LCOH values are above global cost targets, projected reductions in both turbine and electrolyzer systems suggest that Türkiye can reach LCOH values below €2/kg H₂ hydrogen with targeted policy support and technology investment.

This thesis study provides a detailed spatial assessment of wind to hydrogen production in Türkiye, bridging modeling depth with policy relevance. While some simplifications were necessary, the methodology enables replication and adaptation for other renewable configurations or regional planning studies.

The integration of hourly data, city-level analysis and technoeconomic modeling offers a strong foundation for future research. With growing interest in green hydrogen, Türkiye hold substantial promise as a regional leader if strategic and informed steps are taken now.

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BIOGRAPHY

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PUBLICATIONS AND PRESENTATIONS FROM THE THESIS

[1] Sert Engin, Elif ve Özdemir, Murat. Karadaki Rüzgâr Çiftliklerinden Hidrojen Üretiminin Tekno Ekonomik İncelenmesi: Türkiye İçin Bir Fizibilite Analizi. Presented at: 9th GTU Graduate Research Symposium, Gebze Technical University, Gebze, Kocaeli. May 26–27, 2025.



APPENDICES

APPENDIX-A: MONTHLY AVERAGE ERA5 WIND SPEEDS FOR SELECTED CITIES

Month/City	İzmir	Bolu	Eskişehir	Ardahan	Bursa	Mersin	Diyarbakır
January	3.50	2.83	3.50	2.94	2.85	4.07	2.51
February	3.65	2.61	3.42	3.05	2.67	3.24	2.40
March	3.62	2.37	3.71	3.14	2.65	3.56	2.62
April	3.47	2.45	3.83	2.97	2.55	2.91	2.44
May	3.10	2.10	3.54	2.69	2.52	2.81	2.84
June	3.51	2.13	3.63	2.33	2.58	2.94	2.98
July	4.53	2.32	3.92	2.43	3.12	3.01	3.32
August	3.60	2.14	3.53	2.35	3.03	3.13	2.45
September	3.53	2.02	3.17	2.35	2.79	2.70	2.43
October	3.37	2.00	2.85	2.41	2.72	2.79	2.34
November	3.30	2.54	3.32	2.75	2.80	3.28	2.15
December	3.06	2.68	3.05	2.81	2.66	3.76	2.10

APPENDIX-B: PROBABILITY DISTRIBUTION FIT PARAMETERS BY CITY

City	k	c (m/s)	RMSE
Adana	2.07	4.80	0.0040
Adıyaman	2.00	5.21	0.0044
Afyonkarahisar	1.93	5.37	0.0101
Ağrı	1.87	5.39	0.0121
Aksaray	1.91	5.15	0.0091
Amasya	1.94	4.57	0.0092
Ankara	2.08	4.84	0.0102
Antalya	1.73	4.49	0.0086
Ardahan	2.16	5.28	0.0088
Artvin	1.98	3.86	0.0043
Aydın	1.96	5.18	0.0079
Balıkesir	1.97	4.12	0.0047
Bartın	1.97	4.12	0.0047
Batman	1.60	4.46	0.0064
Bayburt	1.87	4.92	0.0136
Bilecik	2.02	4.64	0.0077
Bingöl	2.27	5.19	0.0082
Bitlis	1.84	5.39	0.0065
Bolu	1.95	4.54	0.0036
Burdur	1.93	4.81	0.0075
Bursa	2.12	4.85	0.0055
Çanakkale	2.03	6.92	0.0044
Çankırı	1.83	4.45	0.0104
Çorum	1.88	4.56	0.0058
Denizli	2.15	4.66	0.0080
Diyarbakır	1.73	4.57	0.0085
Düzce	2.00	3.80	0.0048
Edirne	1.87	6.28	0.0058
Elazığ	1.71	4.93	0.0041
Erzincan	2.46	5.12	0.0050

City	k	c (m/s)	RMSE
Erzurum	2.01	5.01	0.0107
Eskişehir	2.08	4.93	0.0114
Gaziantep	2.18	5.79	0.0060
Giresun	1.91	4.48	0.0040
Gümüşhane	1.93	4.88	0.0048
Hakkâri	2.01	5.03	0.0044
Hatay	1.92	5.68	0.0075
Mersin	1.83	5.15	0.0043
Iğdır	2.37	4.86	0.0068
Isparta	2.16	5.54	0.0068
Istanbul	2.15	6.53	0.0023
İzmir	2.04	6.38	0.0098
Kahramanmaraş	2.48	5.34	0.0067
Karabük	2.21	3.92	0.0052
Karaman	1.62	5.51	0.0064
Kars	2.09	5.31	0.0111
Kastamonu	2.19	4.36	0.0068
Kayseri	2.31	5.59	0.0065
Kilis	2.13	5.65	0.0112
Kırıkkale	1.98	4.91	0.0064
Kırklareli	2.03	6.21	0.0046
Kırşehir	1.85	4.96	0.0084
Kocaeli	2.09	4.97	0.0062
Konya	1.72	5.13	0.0131
Kütahya	1.95	5.22	0.0098
Malatya	1.75	5.35	0.0064
Manisa	1.85	5.20	0.0115
Mardin	2.06	5.50	0.0092
Muğla	1.81	4.97	0.0068
Muş	1.62	4.62	0.0071
Nevşehir	1.77	4.98	0.0085
Niğde	1.90	5.16	0.0057
Ordu	2.02	5.11	0.0033
Osmaniye	2.02	4.45	0.0044
Rize	1.87	3.43	0.0066
Sakarya	2.03	4.45	0.0046
Samsun	1.91	4.76	0.0044
Urfa	1.95	5.49	0.0069
Siirt	2.23	4.48	0.0097
Sinop	1.94	4.46	0.0050
Şırnak	2.20	4.55	0.0114
Sivas	1.75	5.66	0.0085
Tekirdağ	2.04	6.40	0.0029
Tokat	2.16	5.08	0.0078
Trabzon	1.78	4.03	0.0059
Tunceli	2.24	4.26	0.0101
Uşak	2.02	5.28	0.0056
Van	1.96	5.62	0.0072
Yalova	2.21	5.46	0.0044
Yozgat	1.94	5.27	0.0093
Zonguldak	1.94	3.93	0.0047

APPENDIX-C: WIND SPEED BIN DISTRIBUTIONS AND CORRESPONDING ENERGY OUTPUT FOR ÇANAKKALE

Wind Speed (m/s)	Turbine Output (kW)	Weibull PDF	Expected hours per year	Energy (kwh)
1E-10	0	1.108E-12	9.223E-09	0.000E+00
0.5	0	9.807E-03	8.162E+01	0.000E+00
1	0	1.967E-02	1.637E+02	0.000E+00
1.5	0	2.908E-02	2.420E+02	0.000E+00
2	0	3.769E-02	3.136E+02	0.000E+00
2.5	0	4.525E-02	3.766E+02	0.000E+00
3	88	5.155E-02	4.290E+02	3.775E+04
3.5	186	5.645E-02	4.698E+02	8.739E+04
4	310	5.989E-02	4.984E+02	1.545E+05
4.5	466	6.186E-02	5.148E+02	2.399E+05
5	657	6.241E-02	5.194E+02	3.412E+05
5.5	892	6.165E-02	5.131E+02	4.577E+05
6	1168	5.974E-02	4.972E+02	5.807E+05
6.5	1496	5.687E-02	4.732E+02	7.080E+05
7	1876	5.322E-02	4.429E+02	8.309E+05
7.5	2303	4.901E-02	4.079E+02	9.394E+05
8	2761	4.445E-02	3.699E+02	1.021E+06
8.5	3227	3.972E-02	3.305E+02	1.067E+06
9	3668	3.498E-02	2.911E+02	1.068E+06
9.5	4075	3.037E-02	2.528E+02	1.030E+06
10	4452	2.602E-02	2.165E+02	9.639E+05
10.5	4762	2.199E-02	1.830E+02	8.713E+05
11	4998	1.833E-02	1.526E+02	7.626E+05
11.5	5165	1.509E-02	1.256E+02	6.487E+05
12	5253	1.226E-02	1.020E+02	5.361E+05
12.5	5298	9.838E-03	8.187E+01	4.337E+05
13	5300	7.793E-03	6.486E+01	3.437E+05
13.5	5300	6.097E-03	5.074E+01	2.689E+05
14	5300	4.711E-03	3.920E+01	2.078E+05
14.5	5300	3.596E-03	2.992E+01	1.586E+05
15	5300	2.711E-03	2.256E+01	1.196E+05
15.5	5300	2.019E-03	1.680E+01	8.905E+04
16	5300	1.486E-03	1.236E+01	6.553E+04
16.5	5300	1.080E-03	8.988E+00	4.764E+04
17	5300	7.759E-04	6.457E+00	3.422E+04
17.5	5300	5.507E-04	4.583E+00	2.429E+04
18	5300	3.863E-04	3.215E+00	1.704E+04
18.5	5300	2.677E-04	2.228E+00	1.181E+04
19	5300	1.834E-04	1.526E+00	8.088E+03

Wind Speed (m/s)	Turbine Output (kW)	Weibull PDF	Expected hours per year	Energy (kwh)
19.5	5300	1.241E-04	1.033E+00	5.475E+03
20	5300	8.304E-05	6.911E-01	3.663E+03
20.5	5300	5.490E-05	4.569E-01	2.422E+03
21	5300	3.587E-05	2.986E-01	1.582E+03
21.5	5300	2.317E-05	1.928E-01	1.022E+03
22	5300	1.479E-05	1.231E-01	6.523E+02

APPENDIX-D: MONTHLY OUTPUT FOR ÇANAKKALE (20% CURTAILMENT)

Month	Wind speed (m/s)	AEP per turbine (kWh)	Total Energy (kWh)	Electrolyzer Cap. (kWh)	Used Energy (kWh)	Curtailed ment (kWh)	H ₂ Output (kg)
Jan.	6.86	1.47E+06	3.82E+09	2.62E+09	2.62E+09	1.19E+09	5.12E+07
Feb.	6.64	1.25E+06	3.26E+09	2.37E+09	2.37E+09	8.88E+08	4.62E+07
Mar.	6.11	1.20E+06	3.11E+09	2.62E+09	2.62E+09	4.88E+08	5.12E+07
Apr.	5.41	9.22E+05	2.40E+09	2.54E+09	2.40E+09	0.00E+00	4.68E+07
May	5.31	9.07E+05	2.36E+09	2.62E+09	2.36E+09	0.00E+00	4.60E+07
June	5.07	7.59E+05	1.97E+09	2.54E+09	1.97E+09	0.00E+00	3.85E+07
July	6.36	1.25E+06	3.26E+09	2.62E+09	2.62E+09	6.35E+08	5.12E+07
Aug.	6.50	1.33E+06	3.45E+09	2.62E+09	2.62E+09	8.25E+08	5.12E+07
Sep.	6.29	1.22E+06	3.16E+09	2.54E+09	2.54E+09	6.24E+08	4.95E+07
Oct.	6.55	1.35E+06	3.51E+09	2.62E+09	2.62E+09	8.83E+08	5.12E+07
Nov.	6.71	1.37E+06	3.56E+09	2.54E+09	2.54E+09	1.02E+09	4.95E+07
Dec.	6.58	1.37E+06	3.55E+09	2.62E+09	2.62E+09	9.27E+08	5.12E+07

APPENDIX-E: AVAILABLE LAND AREA, WIND CAPACITY and NO OF TURBINES DEPLOYED PER CITY

City	Available Area (km ²)	Wind capacity	No of turbines
Adana	179.74	952.622	179
Adıyaman	239.38	1268.714	239
Afyonkarahisar	162.3	860.19	162
Ağrı	143.38	759.914	143
Aksaray	63.6	337.08	12
Amasya	228	1208.4	228
Ankara	485	2570.5	485
Antalya	234	1240.2	234
Ardahan	2	10.6	2
Artvin	2	10.6	2

City	Available Area (km ²)	Wind capacity	No of turbines
Aydın	504.75	2675.175	505
Balıkesir	2765.5	14657.15	2765
Bartın	12	63.6	12
Batman	1.7	9.01	2
Bayburt	0	0	0
Bilecik	61.73	327.169	62
Bingöl	34	180.2	34
Bitlis	4.4	23.32	4
Bolu	4.4	23.32	4
Burdur	11.6	61.48	12
Bursa	732	3879.6	732
Çanakkale	2602.51	13793.3	2602
Çankırı	63.07	334.271	63
Çorum	31.23	165.519	31
Denizli	47.71	252.863	48
Diyarbakır	127.01	673.153	127
Düzce	9.5	50.35	10
Edirne	694.02	3678.306	694
Elazığ	205.68	1090.104	206
Erzincan	76.54	405.662	77
Erzurum	9.5	50.35	9
Eskişehir	8	42.4	8
Gaziantep	53.38	282.914	53
Giresun	32	169.6	32
Gümüşhane	0	0	0
Hakkâri	6	31.8	6
Hatay	682	3614.6	682
Iğdır	0	0	0
Isparta	284	1505.2	284
İstanbul	835	4425.5	835
İzmir	2370	12561	2370
Kahramanmaraş	390	2067	390
Karabük	14	74.2	14
Karaman	186	985.8	186
Kars	0	0	0
Kastamonu	97	514.1	97
Kayseri	355	1881.5	355
Kilis	7	37.1	7
Kırıkkale	22	116.6	22
Kırklareli	700	3710	700
Kırşehir	53	280.9	53
Kocaeli	15	79.5	15
Konya	372	1971.6	372

City	Available Area (km ²)	Wind capacity	No of turbines
Kütahya	38	201.4	38
Malatya	279	1478.7	279
Manisa	1060	5618	1060
Mardin	101	535.3	101
Mersin	706	3741.8	706
Muğla	1034	5480.2	1034
Muş	11	58.3	11
Nevşehir	1	5.3	1
Niğde	19	100.7	19
Ordu	429	2273.7	429
Osmaniye	135	715.5	135
Rize	0	0	0
Sakarya	0	0	0
Samsun	1044	5533.2	1044
Siirt	3	15.9	3
Sinop	298	1579.4	298
Şırnak	0	0	0
Sivas	328	1738.4	328
Tekirdağ	925	4902.5	925
Tokat	566	2999.8	566
Trabzon	5	26.5	5
Tunceli	3	15.9	3
Urfa	0	0	0
Uşak	38	201.4	38
Van	28	148.4	28
Yalova	106	561.8	106
Yozgat	215	1139.5	215
Zonguldak	10	53	10

APPENDIX-F: HYDROGEN OUTPUT FOR 0% AND 20% CURTAILMENT FOR EACH CITY

City	Hydrogen output (0 Curtailment) (Mt)	Hydrogen output (20% Curtailment) (Mt)
Adana	0.020	0.016
Adıyaman	0.035	0.028
Afyonkarahisar	0.025	0.020
Ağrı	0.018	0.018
Aksaray	0.002	0.001
Amasya	0.024	0.019
Ankara	0.055	0.044
Antalya	0.025	0.020

City	Hydrogen output (0 Curtailment) (Mt)	Hydrogen output (20% Curtailment) (Mt)
Ardahan	0.000	0.000
Artvin	0.000	0.000
Aydın	0.072	0.058
Balıkesir	0.623	0.498
Bartın	0.001	0.001
Batman	0.000	0.000
Bayburt	0.000	0.000
Bilecik	0.007	0.005
Bingöl	0.005	0.004
Bitlis	0.001	0.001
Bolu	0.000	0.000
Burdur	0.001	0.001
Bursa	0.087	0.070
Çanakkale	0.730	0.584
Çankırı	0.006	0.005
Çorum	0.003	0.003
Denizli	0.005	0.004
Diyarbakır	0.014	0.011
Düzce	0.001	0.001
Edirne	0.160	0.128
Elazığ	0.028	0.023
Erzincan	0.009	0.007
Erzurum	0.001	0.001
Eskişehir	0.001	0.001
Gaziantep	0.010	0.008
Giresun	0.003	0.003
Gümüşhane	0.000	0.000
Hakkâri	0.001	0.001
Hatay	0.128	0.102
Iğdır	0.104	0.083
Isparta	0.000	0.000
Istanbul	0.046	0.036
İzmir	0.205	0.164
Kahramanmaraş	0.556	0.445
Karabük	0.055	0.044
Karaman	0.001	0.001
Kars	0.034	0.027
Kastamonu	0.000	0.000
Kayseri	0.008	0.006
Kilis	0.057	0.045
Kırıkkale	0.001	0.001
Kırklareli	0.003	0.002
Kırşehir	0.154	0.123

City	Hydrogen output (0 Curtailment) (Mt)	Hydrogen output (20% Curtailment) (Mt)
Kocaeli	0.007	0.006
Konya	0.002	0.002
Kütahya	0.055	0.044
Malatya	0.006	0.004
Manisa	0.046	0.036
Mardin	0.161	0.129
Mersin	0.016	0.013
Muğla	0.137	0.109
Muş	0.001	0.001
Nevşehir	0.000	0.000
Niğde	0.003	0.002
Ordu	0.058	0.047
Osmaniye	0.013	0.010
Rize	0.000	0.000
Sakarya	0.000	0.000
Samsun	0.125	0.100
Siirt	0.000	0.000
Sinop	0.000	0.000
Şırnak	0.029	0.023
Sivas	0.000	0.000
Tekirdağ	0.062	0.049
Tokat	0.222	0.177
Trabzon	0.073	0.058
Tunceli	0.000	0.000
Urfa	0.000	0.000
Uşak	0.006	0.005
Van	0.005	0.004
Yalova	0.017	0.014
Yozgat	0.033	0.026
Zonguldak	0.001	0.001

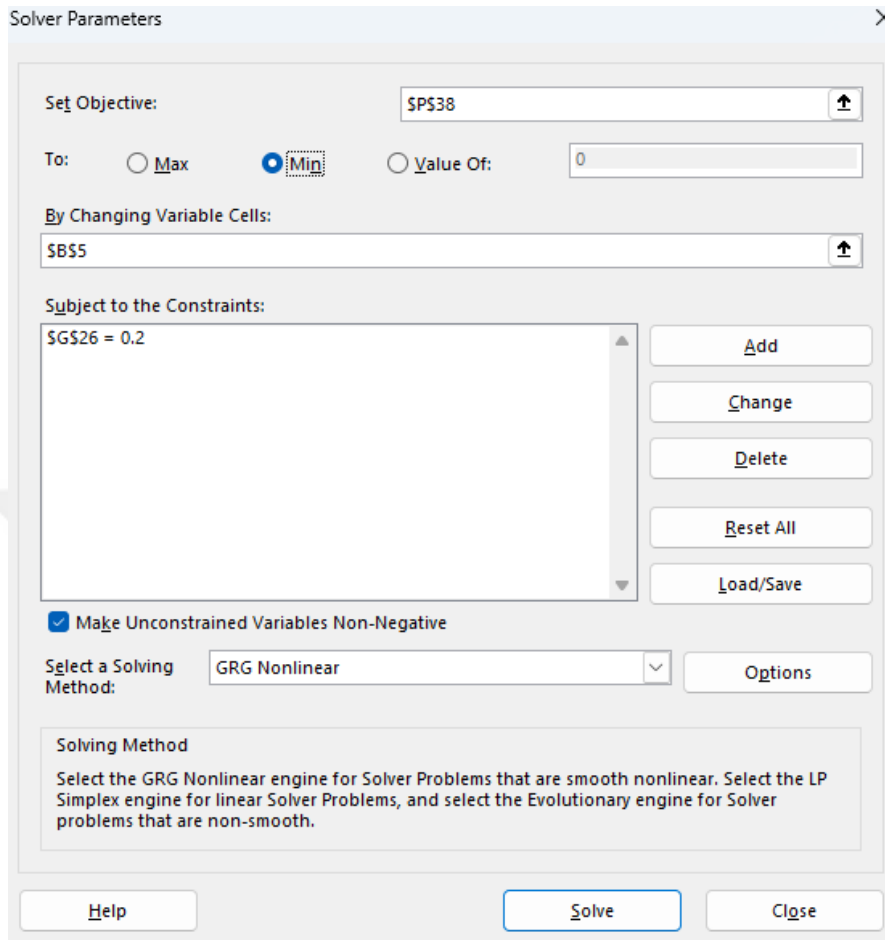
APPENDIX-G: CAPEX and OPEX ESTIMATIONS FOR 2025

CAPEX (Assumption) (E/kW)	1050
Lifetime	25
O&M Cost (E/MWh)	35
CRF	0.093678779
CAPEX (Electrolyzer) (E/kW)	2500
Stack durability	80000
Stack degradation per 1000 h	0.12
OPEX Electrolyzer	2% CAPEX

APPENDIX-H: LCOE, LCOH and HYDROGEN OUTPUT FOR DIFFERENT SCENARIOS

City	LCOE 2025 (€)	LCOH 2025 (€)	LCOE 2035 (€)	LCOH 2035 (€)	LCOE 2050 (€)	LCOH 2050 (€)	H ₂ output 2035 (Mt)	H ₂ output 2050 (Mt)
Bursa	0.035	3.702	0.030	2.673	0.021	1.677	0.075	0.080
Balıkesir	0.035	3.712	0.030	2.679	0.021	1.681	0.537	0.575
Sinop	0.035	3.712	0.030	2.681	0.021	1.682	0.025	0.027
Edirne	0.035	3.721	0.030	2.685	0.021	1.685	0.137	0.147
İzmir	0.035	3.726	0.030	2.689	0.021	1.687	0.479	0.514
Kırklareli	0.035	3.733	0.030	2.693	0.021	1.689	0.133	0.142
Erzincan	0.035	3.733	0.030	2.697	0.021	1.692	0.008	0.009
Çanakkale	0.035	3.753	0.030	2.706	0.021	1.697	0.629	0.674
Isparta	0.035	3.756	0.030	2.709	0.021	1.699	0.039	0.042
Adana	0.035	3.755	0.030	2.709	0.021	1.699	0.017	0.019
İstanbul	0.035	3.759	0.030	2.710	0.021	1.700	0.177	0.190
Kayseri	0.035	3.768	0.030	2.716	0.021	1.703	0.049	0.052
Yalova	0.035	3.774	0.030	2.721	0.021	1.707	0.015	0.016
Ağrı	0.035	3.777	0.030	2.723	0.021	1.708	0.020	0.021
Uşak	0.036	3.774	0.031	2.725	0.021	1.710	0.005	0.005

APPENDIX-I: EXCEL SOLVER FUNCTION SETTING FOR LCOH AND ELECTROLYZER SIZE OPTIMIZATION



The image shows the Excel Solver Parameters dialog box. The 'Set Objective:' field is set to '\$P\$38'. The 'To:' section has three radio buttons: 'Max' (unselected), 'Min' (selected), and 'Value Of:' (unselected). The 'Value Of:' field is set to '0'. The 'By Changing Variable Cells:' field is set to '\$B\$5'. The 'Subject to the Constraints:' list contains one constraint: '\$G\$26 = 0.2'. To the right of this list are buttons for 'Add', 'Change', 'Delete', 'Reset All', and 'Load/Save'. Below the constraints list is a checked checkbox labeled 'Make Unconstrained Variables Non-Negative'. The 'Select a Solving Method:' dropdown is set to 'GRG Nonlinear', with an 'Options' button next to it. A 'Solving Method' text box provides instructions: 'Select the GRG Nonlinear engine for Solver Problems that are smooth nonlinear. Select the LP Simplex engine for linear Solver Problems, and select the Evolutionary engine for Solver problems that are non-smooth.' At the bottom are buttons for 'Help', 'Solve', and 'Close'.

Solver Parameters

Set Objective:

To: ☐ Max ☒ Min ☐ Value Of:

By Changing Variable Cells:

Subject to the Constraints:

☒ Make Unconstrained Variables Non-Negative

Select a Solving Method: Options

Solving Method

Select the GRG Nonlinear engine for Solver Problems that are smooth nonlinear. Select the LP Simplex engine for linear Solver Problems, and select the Evolutionary engine for Solver problems that are non-smooth.

Help Solve Close

Where:

- P38 is the LCOH cell
- B5 is the electrolyzer capacity cell
- G26 is the percent curtailment cell