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RESEARCH ARTICLE

Airborne Wind Energy Potential in Türkiye: A Study of Wind Resource, Life Cycle Assessment, and Techno-Economic Analysis

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ABSTRACT This paper provides an integrated assessment of Airborne Wind Energy (AWE) systems in Türkiye, evaluating their potential as a future renewable energy source. The study addresses key questions of resource availability, environmental impact, and economic viability through a threefold methodology applied to ten regions: 1) probabilistic wind modeling to accurately characterize high-altitude resources, 2) a comparative life-cycle assessment (LCA) to quantify environmental impacts against conventional turbines, and 3) a techno-economic analysis (TEA) to determine financial viability. Our results indicate that the Gamma distribution generally provides the most accurate model for the high-altitude wind profiles studied ($R^2 > 0.997$). The LCA reveals a compelling environmental case for AWE, with a global warming potential as low as 7.2 gCO_2-eq/kWh in prime locations. The TEA projects a highly competitive levelized cost of electricity (LCOE), ranging from $0.042/kWh in wind-rich areas like Çanakkale to over $0.16/kWh in less ideal sites. With an internal rate of return exceeding 18% in the most favorable regions, the study concludes that AWE systems appear to be a technically promising and economically viable option for Türkiye, capable of matching or even outperforming conventional wind power in select locations.

INDEX TERMS Airborne wind energy, life cycle assessment, techno-economic analysis, wind performance assessment.

I. INTRODUCTION

Rapid advancement of renewable energy technologies has become crucial in addressing the dual challenges of energy security and climate change. Among these technologies, wind energy has emerged as a leading contributor to global renewable energy capacity. However, traditional wind energy systems, predominantly Horizontal Axis Wind Turbines (HAWTs), face limitations in exploiting high-altitude wind resources and adapting to diverse geographical conditions. In this context, Airborne Wind Energy (AWE) systems offer a transformative alternative that harnesses high-altitude wind currents through tethered flying devices such as kites and drones [1]. These systems operate at altitudes where wind speeds are stronger and more consistent, leading to potentially higher energy yields and reduced environmental impacts [2].

Despite their promise, AWE systems remain an underexplored area in terms of performance evaluations. Previous studies have primarily focused on technical feasibility or conceptual analyses, leaving critical gaps in understanding their economic and environmental viability under real-world conditions. The variability of wind speed distributions, especially in complex terrains, further underscores the importance of precise probabilistic modeling to accurately estimate energy production and assess economic performance.

Research on AWE sytems suggests promising developments in renewable energy technology. One study indicates that capital costs could decrease to under $1,000/kW by 2030, with potential capacity factors ranging from 40-60% for different system sizes [3]. Another study highlights that these systems can efficiently operate at wind heights below

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500 meters, with 1-1.5 MW systems considered a realistic target by 2030 [4]. Significant environmental advantages, demonstrating that AWE systems use 40-50% less material compared to traditional turbines and offer a 30-40% lower carbon footprint [5]. Another study further supported these findings, noting a 20% advantage in initial costs and 10-15% higher energy production at high altitudes (200-800 m) [1]. One other study emphasized the potential of these systems in distributed energy networks, estimating a technical potential of 9,029 GW for systems with 227 m tethers [4], while one study noted promising pilot projects with 5 MW systems achieving 60-70% capacity factors, though challenges in control and cost optimization persist [6].

Recent literature indicates that the AWE field is rapidly maturing, with a notable shift from theoretical modeling to the development and testing of physical prototypes [7]. This requires a holistic approach, addressing everything from high-level design archetypes, such as ground-generation and fly-generation platforms [8], to the specific engineering challenges that govern operational safety and efficiency. A significant body of research now focuses on refining core technologies, including sophisticated autonomous control systems to optimize flight paths [9] and safety-aware hybrid control laws [10]. Advanced computational techniques like stroboscopic averaging are being used to model and optimize realistic flight phases [11]. In parallel, detailed analysis of hardware is equally vital, with studies developing methodologies for sizing components like the winch to ensure dynamic stability [12]. As systems move toward long-term autonomous operation, reliability has become a paramount concern, leading to the application of aerospace methodologies like Failure Mode and Effects Analysis (FMEA) and Fault Detection, Isolation, and Recovery (FDIR) systems to improve the robustness of commercial AWE systems [13], [14].

In parallel with these technological advancements, assessment studies have also evolved. Recent comparative Life Cycle Assessments (LCA) have consistently validated the environmental benefits of AWE systems [6], [15], while Techno-Economic Analyses (TEA) are increasingly using the Levelized Cost of Energy (LCOE) to guide system design and optimization [16]. While these targeted advancements are crucial, their practical value must be contextualized through comprehensive regional assessments [17]. This need is echoed by major reports from governmental and international bodies, which have highlighted a persistent gap: a lack of integrated assessments tailored to specific geographic regions to evaluate key cost drivers and market potential [18], [19], [20].

This study addresses this gap by providing an integrated assessment for Türkiye. Our work contributes by: (1) conducting a detailed comparison of a wide suite of wind distribution models beyond the standard Weibull [3]; (2) performing a cradle-to-grave LCA tailored to a specific geographical supply chain; and (3) developing a TEA that is deeply integrated with site-specific resource data and LCA inventories. Accordingly, this investigation is guided by the following core questions: (1) Which high-potential regions in Türkiye offer the most promising wind resources for AWE systems operating at high altitudes? (2) Among a wide array of statistical methods, which distribution models most accurately capture the unique characteristics of these wind regimes? (3) What are the projected life-cycle environmental impacts (GWP and CED) of deploying a representative AWE system in this context? (4) Finally, what is the techno-economic feasibility of these systems across the selected sites, and which locations appear most viable for future investment?

The remainder of this paper is organized as follows. Section II details the methodology. Section III talks about the results of this study and the discussions of these results. Finally, Section IV presents concluding remarks and outlines future research directions.

TABLE 1. AWE systems literature review.

Study	Key Focus	Findings	Region
[3]	Technical Feasibility	Potential cost < $1,000/kW by 2030	40-60%
[4]	System Heights	Efficient below 500m	45-55%
[5]	Life Cycle Analysis	40-50% less material use	N/A
[1]	Cost Analysis	20% lower initial costs	45-55%
[4]	Long-term Viability	10-15% lower distributed energy costs	N/A
[6]	Multi-megawatt Systems	Pilot projects show promise	60-70%

II. METHODOLOGY

A. WIND DATA ASSESSMENT

The availability of high-quality wind data is crucial for accurately assessing the energy potential and economic feasibility of renewable energy projects. For AWE systems, this requirement is even more pronounced, as these systems operate at altitudes where wind characteristics differ significantly from ground-level measurements. This study conducts a detailed evaluation of wind data in ten strategically chosen cities in Türkiye, characterized by their high wind energy potential and diverse meteorological conditions. The assessment aims to provide a precise characterization of wind resources through advanced probabilistic models, supporting reliable predictions of energy yield and economic performance.

The following ten cities were selected for the study based on their wind energy potential, infrastructure readiness, and geographical diversity: Afyonkarahisar, Aydın, Balıkesir, Bursa, Çanakkale, Hatay, İzmir, Kırklareli, Manisa, and Sinop. The selection rationale has been highlighted in Table 2.

The cities were selected to represent a balance of coastal and inland regions, capturing the variability in wind speeds and conditions across Türkiye. The diversity ensures that the study's findings are robust and applicable to a wide range of geographical contexts.

To evaluate the wind energy potential in these regions, wind speed data was obtained from the Global Wind Atlas and NASA databases. The dataset consists of hourly average

TABLE 2. Case study locations and selection criteria.

City	Avg. Wind Speed - 100m (m/s)	Rationale for Selection
Afyonkarahisar	6.7	Inland city with untapped wind energy potential and strategic location for energy transmission.
Aydın	4.9	Proximity to renewable energy projects and high regional wind speeds.
Balıkesir	7.4	Significant wind farm deployment and favorable wind conditions.
Bursa	6.5	Industrial hub with increasing interest in wind energy projects.
Çanakkale	9.6	Strategically located near coastal regions with consistent wind speeds.
Hatay	6.4	Prominent wind corridor and potential for AWE deployment.
İzmir	7.6	High wind energy capacity and established renewable energy infrastructure.
Kırklareli	7.8	Moderate wind speeds with proximity to major energy transmission lines and growing renewable initiatives.
Manisa	6.2	Strong wind potential in inland areas and growing interest in renewables.
Sinop	6.1	Coastal city with high-altitude wind resources and low population density, ideal for AWE systems.

wind speeds covering the period from January 2024 to January 2025. This timeframe provides a complete annual cycle, ensuring that all seasonal variations are captured in the analysis. Data was standardized to a 100-meter height using the power law:

$$V(z) = V(z_0)\left(\frac{z}{z_0}\right)^{\alpha} \tag{1}$$

where z is the desired height z_0 is the reference height, and α is the surface roughness exponent.

It must be acknowledged, however, that this model is a simplification. The actual wind profile can be affected by atmospheric stability, thermal effects, and local topography, which may lead to deviations from the power law prediction [21], [22]. Since direct high-altitude measurements (e.g., from LIDAR) were not available for these sites, the extrapolation introduces a key source of uncertainty in the energy production estimates and is therefore considered a limitation of this study.

Advanced statistical models, including Weibull, Burr, Gamma, and Rayleigh distributions, were applied to characterize the wind speed distribution. The performance of each model was evaluated using goodness-of-fit metrics such as the Chi-square test, Root Mean Square Error (RMSE), R^2, and Wind Energy Error (WEE). In this study, the best-fit model for each site was determined as the distribution yielding the highest R^2 together with the lowest error statistics (WEE, RMSE, and Chi-square).

While other model selection criteria, such as the Akaike Information Criterion (AIC), are valuable for penalizing model complexity, our focus here was on metrics that most directly quantify the accuracy of the fit for the specific purpose of wind energy estimation.

The Annual Energy Production (AEP) was estimated for each city using the best-fitting distribution:

$$AEP = 0.5 \cdot \rho \cdot A \cdot \sum_{i=1}^{n} V_i^3 \cdot h_i \tag{2}$$

where ρ is air density, A is the rotor area, V_i is wind speed, and h_i is the probability of V_i. Also, h_i represents the probability of occurrence for the wind speed in the i^{th} bin (V_i), derived from the probability density function (PDF) of the best-fit statistical distribution identified for that specific city. Economic parameters, such as capacity factor, were integrated with wind speed data to evaluate the potential for AWE systems.

FIGURE 1. Location of case study cities.

TABLE 3. Parameter estimation methods used in this study.

Parameter Estimation Method	Abbreviation	Source
Graphical Method	GM	[23]
Maximum Likelihood Method	MLM	[24]
Modified Maximum Likelihood Method	MMLM	[25]
Energy Pattern Factor Method	EPFM	[26]
Wind Energy Intensification Method	WEIM	[27]
Justus Moment Method	JMM	[28]
Power Density Method	PD	[29]
Lysen Method	LM	[30]
Method of Moments	MOM	[31]
Mabchour's Method	MMAB	[32]
Alternative Maximum Likelihood Method	AML	[33]
Novel Energy Pattern Factor Method	NEPFM	[28]
Least Squares Method	LSM	[34]
Rayleigh Distribution	RAY	[35]
Gamma Distribution	GAM	[36]
Burr Distribution	BUR	[36]

Table 3 outlines the parameter estimation methods employed to derive the scale and shape parameters of the Weibull distribution, as well as other distributions, namely Burr, Gamma, and Rayleigh. A MATLAB code was developed to facilitate the comparative analysis of these methods. Initially, their performance was benchmarked against real wind data measurements to assess their accuracy, as depicted in Fig. 5.

A key aspect of our approach was the detailed evaluation of numerous parameter estimation methods. Many studies in this area tend to pre-select a few common distributions, which is certainly a reasonable starting point. However, it appeared that this might not be sufficient for this particular study. Türkiye's geography is quite varied, with distinct wind patterns in its coastal, inland, and mountainous areas. A one-size-fits-all model, or even a small selection, could potentially overlook the distribution that best fits a specific location's unique climate profile. By testing a wider set of 16 methods, the goal was to avoid this potential bias and identify the most suitable model for each region. This, in turn, should give greater confidence in the energy production and economic projections that follow.

B. LIFE-CYCLE ASSESSMENT

The environmental sustainability of renewable energy systems is becoming increasingly important as global efforts intensify to combat climate change. While AWE systems promise reduced material consumption and enhanced efficiency, an understanding of their environmental impacts remains underexplored. Life Cycle Assessment (LCA) provides a robust framework to evaluate the environmental performance of energy systems by analyzing the environmental impacts associated with all stages of their life cycle, from raw material extraction to decommissioning.

This paper employs a detailed Life Cycle Assessment (LCA) approach to compare the environmental impacts of AWE systems with conventional Horizontal Axis Wind Turbines (HAWTs). By assessing key environmental indicators such as Global Warming Potential (GWP) and Cumulative Energy Demand (CED), the analysis aims to quantify the potential environmental advantages of AWE systems and identify areas for improvement.

For LCA of the proposed AWE deployment, an initial evaluation of available LCA software was conducted to identify the most suitable tool. While several programs exist, many proved incompatible or lacked the required databases for AWE-specific analyses due to their emerging nature. This process involved two main steps: software selection and data acquisition. Given the limited availability of AWE data, a systematic approach was adopted, involving extensive literature research, data extraction from relevant sources adhering to predefined quality criteria, critical verification for accuracy and reliability, and compilation into a structured dataset.

Six programs have been evaluated, namely; GaBi, openLCA, SimaPro, Umberto, Ecochain, and Umberto NXT. The literature suggests Umberto NXT, SimaPro, and GaBi as commonly used for AWE systems. Ultimately, OpenLCA was selected based on its widespread adoption in both renewable and wind energy LCA studies.

While established commercial packages such as SimaPro and GaBi are widely used, they are often optimized for mature industries with well-documented supply chains. Modeling an emerging technology like AWE presents a different sort of challenge, as standardized life-cycle inventories for many of its specialized components are not yet available. For this reason, we selected OpenLCA for our analysis. Its open-source platform removes the cost barriers associated with commercial licenses, a practical advantage in an academic setting. More importantly, it offers a high degree of flexibility, which was necessary for customizing the life cycle inventory to reflect the materials and processes for AWE systems. This adaptability, combined with its compatibility with transparent and citable databases like Ecoinvent, made it a more suitable choice for this research than other available tools.

Each city's scaling factors reflect variations in wind speed, logistics, and material requirements, directly impacting the environmental metrics of AWE systems. These factors include:

Wind Speed (Capacity Factor Scaling): Higher average wind speeds lead to greater energy output and reduced environmental impact per kWh. Capacity factors (CF) for each city are scaled proportionally to wind speeds:

$$CF_i = CF_{\text{base}} \times \frac{V_i}{V_{\text{base}}} \tag{3}$$

where CF_{base} and V_{base} are the reference capacity factor and wind speed.

Material transportation distance: proximity to manufacturing hubs influences emissions and energy use in transportation. For each city, material-related emissions were scaled by transportation distance:

$$E_{\text{transport}} = M \times d_i \times EF \tag{4}$$

where $\boldsymbol{M}$ is material weight, d_i is the distance to the site, and $\boldsymbol{EF}$ is the emissions factor.

Regional energy grid: electricity used during manufacturing, installation, and operation depends on the local grid's carbon intensity. The Global Warming Potential (GWP) was adjusted using regional energy mix data:

$$GWP_i = GWP_{\text{base}} \times \frac{CI_i}{CI_{\text{base}}} \tag{5}$$

where CI_i and CI_{base} are the carbon intensities of the city's grid and the baseline grid.

Site-specific infrastructure: installation and maintenance impacts were scaled based on the infrastructure available in each city, with remote areas requiring more energy-intensive logistics.

Incorporating city-specific scaling factors into the LCA framework enhances the accuracy and relevance of environmental impact assessments for AWE systems. By accounting for variations in wind speed, material transport, and energy grid intensity, this study provides assessment of the environmental performance of AWE systems across diverse geographic regions. These insights guide the sustainable deployment of AWE technology and emphasize the need for location-specific optimization in design and logistics.

The LCA methodology for this study followed the standardized framework provided by ISO 14040 and ISO 14044,

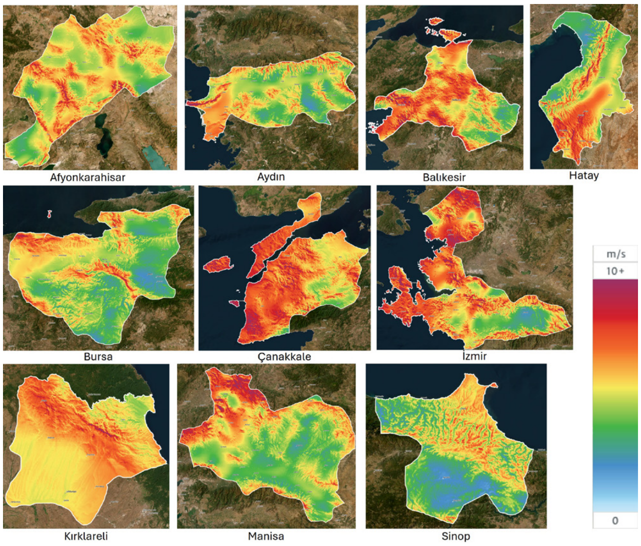

FIGURE 2. Wind energy potential of case locations at 100 m elevation.

encompassing the four main stages: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation (Fig. 3).

Definition of goal and scope: the goal was to evaluate the environmental impacts of AWE systems across ten wind-rich regions in Türkiye and compare them to HAWTs [37]. The system boundary included material extraction, manufacturing, transportation, installation, operation, maintenance, and end-of-life disposal or recycling.

Life cycle inventory (LCI): detailed data was collected on materials, energy inputs, and emissions for both AWE and HAWT systems [38]. Key components such as tether materials (e.g., Dyneema, a brand of Ultra-High-Molecular-Weight Polyethylene), kite structure (e.g., Carbon-Fiber Reinforced Polymer (CFRP)), and ground-based infrastructure were analyzed for AWE systems. For HAWTs, blades (GFRP), towers (steel), and nacelle components were included. Data sources included primary data from manufacturers, secondary data from databases (e.g., Ecoinvent), and literature.

Life cycle impact assessment (LCIA): environmental impact categories focused on *Global Warming Potential (GWP),* quantifying greenhouse gas emissions in CO_2-equivalents. *Cumulative Energy Demand (CED),* total primary energy consumption across the life cycle.

Results were normalized and compared across both systems to identify environmental hotspots and improvement opportunities [39].

Life cycle assessment provides critical information on the sustainability of AWE systems. Unlike traditional performance metrics such as energy yield or economic returns, LCA uncovers hidden environmental costs that may not be evident during the operational phase. These assessments are essential for guiding policy and decision-making through governments and stakeholders that can make informed decisions about renewable energy investments by considering the full environmental impact. Identifying improvement opportunities by pinpointing areas with high environmental burdens, LCA helps manufacturers and researchers optimize designs, materials, and processes. Supporting circular economy initiatives with the recycling potential of components, particularly in high-value materials like CFRP, can significantly reduce environmental impacts and enhance system sustainability.

While a Life Cycle Assessment can encompass a wide range of environmental indicators, this study focuses on Global Warming Potential (GWP) and Cumulative Energy Demand (CED). This choice was made for a couple of reasons. First, these two metrics are arguably the most critical for evaluating energy systems, as they directly address the core challenges of climate change and primary energy consumption [40], [41]. Second, several studies have suggested that CED can serve as a strong proxy indicator for a wider array of environmental impacts [42]. Because so many environmental burdens, from acidification to resource depletion, are linked to energy-intensive activities like material extraction and processing, CED often shows a good correlation with these other categories [42]. Given that AWE is an emerging technology, we felt that concentrating on these two well-documented and highly relevant indicators would provide a clearer and more robust assessment than broadening the scope to include other categories where data for novel components might be less mature or carry higher uncertainty [43].

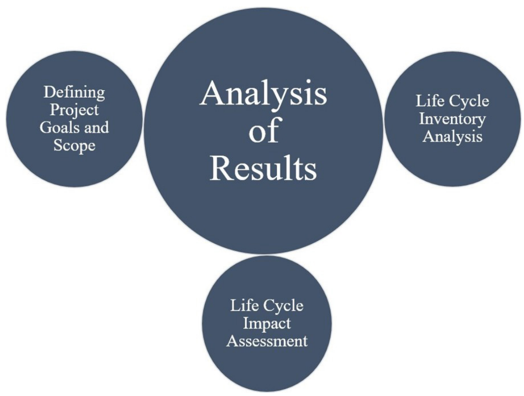

FIGURE 3. Life cycle assessment stages.

C. TECHNO-ECONOMIC ASSESSMENT

Having established the environmental credentials of AWE systems through the Life Cycle Assessment, which suggests a compelling case based on metrics like Global Warming Potential, an important question remains: can this environmental promise be delivered in an economically viable manner? A technology's sustainability is ultimately a function of both its ecological footprint and its financial feasibility; without a sound business case, even the most environmentally benign technology is unlikely to achieve widespread deployment. Therefore, the Techno-Economic Assessment (TEA) serves as the necessary next step, evaluating whether the operational and material advantages identified in the LCA translate into a competitive cost of energy. This section aims to target this gap, moving from environmental impact to investment viability.

A techno-economic assessment (TEA) is critical for evaluating the viability of renewable energy systems, bridging the gap between technical performance and economic feasibility. For AWE systems, this evaluation is particularly important due to their novel design, unique operational characteristics, and potential for disruptive innovation. Unlike traditional HAWTs, AWE systems rely on lightweight structures and high-altitude wind resources, which influence both capital and operational expenditures.

To ensure a consistent basis for the LCA and TEA, a ‘‘reference AWE system’’ was defined based on parameters representative of a pre-commercial, utility-scale concept. The system is a ground-generation (GG) model, where a tethered aircraft flies in crosswind patterns and the resulting tensile force drives a generator on the ground. This architecture is common for systems targeting the megawatt class. The key technical specifications are detailed in Table 4.

TABLE 4. Reference AWE system technical parameters.

Parameter	Value	Unit	Source/Justification
System Type	Fixed-Wing	–	A hypothetical commercial system [6]
Rated Power	5.0	MW	Literature examples with similar capacity [6]
Kite/Aircraft Material	CFRP	–	Primary structural material from inventory analysis
Tether Material	Dyneema (UHMWPE)*	–	Standard for high tensile strength from inventory analysis
Operating Altitude	100–500	m	Typical AWE operational window
Assumed Lifespan	20	Years	Standard for renewable energy projects

* Ultra-High-Molecular-Weight Polyethylene

This study presents a detailed TEA of AWE systems across ten wind-rich regions in Türkiye. By integrating metrics such as Net Present Value (NPV), Levelized Cost of Electricity (LCOE), Internal Rate of Return (IRR), and payback period, this study provides a robust economic analysis to support decision-making for stakeholders. The analysis is contextualized with comparisons to HAWTs, emphasizing the cost-effectiveness and market competitiveness of AWE technology.

The TEA was conducted using a systematic approach that integrates wind data, operational parameters, and financial metrics. The key steps are outlined below:

A critical input for the TEA is the capacity factor (CF), which reflects the actual energy output of the system relative to its maximum potential. To ensure the economic analysis is directly tied to the local wind resource potential, the CF for each city was dynamically calculated. This was based on the Annual Energy Production (AEP) derived from the best-fit wind speed distribution for that specific location. The CF is determined using the formula:

$$CF = \frac{\text{AEP}}{\text{Rated Capacity} \times \text{Hours per Year}} \tag{6}$$

where AEP is in MWh/year, and rated capacity is the maximum power output (MW).

Capital expenditure (CAPEX) is the upfront cost of AWE systems was calculated on a per-MW basis, including manufacturing, installation, and infrastructure costs. Operational expenditure (OPEX) is the annual maintenance and operation costs that were estimated based on system complexity and regional economic factors. Factors affecting both CAPEX and OPEX are mainly installation, maintenance costs and system parts. Main system parts are shown in Fig. 4. A fraction of CAPEX was allocated for end-of-life management, emphasizing recycling and disposal, which are mainly the decommissioning costs. Economic metrics addresses logistical and manufacturing challenges associated with scaling AWE systems to larger capacities.

Net present value (NPV) is calculated as:

$$NPV = \sum_{t=1}^{T} \frac{\text{Net Cash Flow}_t}{(1+r)^t} - \text{Initial Investment} \tag{7}$$

where $\boldsymbol{T}$ is the project lifetime, $\boldsymbol{r}$ is the discount rate, and $NetCashFlow_{\boldsymbol{t}}$ is the revenue minus OPEX in year $\boldsymbol{t}$.

Levelized cost of electricity (LCOE):

$$LCOE = \frac{\sum_{t=1}^{T} \frac{\text{CAPEX}_t + \text{OPEX}_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{\text{AEP}_t}{(1+r)^t}} \tag{8}$$

LCOE provides a normalized cost of energy, enabling comparisons across regions and technologies.

Internal rate of return (IRR) was calculated by finding the discount rate (r) that satisfies:

$$NPV = 0 \tag{9}$$

The payback period was determined by tracking cumulative cash flows to identify the year and fraction of the year when the initial investment is fully recovered.

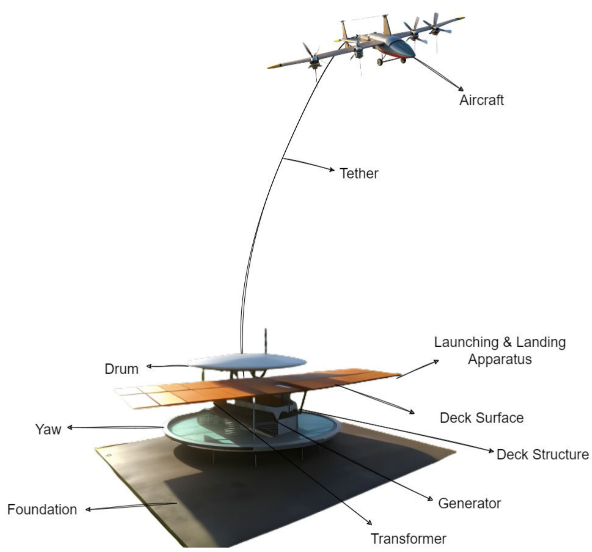

FIGURE 4. Structural components of an AWE plant.

III. RESULTS AND DISCUSSION

A. WIND DATA ASSESSMENT

Fig. 5 and Table 5 provide a detailed breakdown of the results, revealing that the GAM and the PD methods yielded the highest performance. Furthermore, an error analysis was conducted using widely adopted metrics, including WEE, RMSE, R-squared (R^2) and Chi-squared (χ^2). Table 6 presents the comparative error values, with lower values indicating better performance for all metrics except R^2, where higher values are preferred.

The performance of the different methods varied considerably across the ten cities. Table 5 provides a detailed breakdown of these results, showing the number of data points where each method's prediction was closest to the actual measured wind data. As the table illustrates, the Gamma (GAM) and Power Density (PD) methods consistently appear at the top of the rankings, which suggests they are particularly well-suited for modeling the wind profiles in these regions.

To look at this from another angle, a quantitative error analysis was performed. The results are presented in Table 6, which compares all methods across four standard metrics: WEE, RMSE, R-squared, and Chi-squared. The table is organized to help compare the performance metrics for each city. Lower values for WEE, RMSE, and Chi-squared indicate a better fit, while a higher R-squared value is preferable. A quick glance at the table shows that certain methods consistently produce lower error values.

To evaluate the detailed error metrics from the previous table, Table 7 provides a simple ranking of the methods for each city based on their performance for each of the four error metrics. This ranking makes it easier to spot the consistent top performers. For instance, the table highlights that the Gamma (GAM) and Justus (JUS) methods frequently rank first or second across multiple error categories, reinforcing the conclusions drawn from the raw data.

Fig. 6 presents the comparison of the performance of each method based on the data from Fig. 5. The closer the values in Fig. 6 to zero, the better the method performs. This is also highlighted by Table 5. The values of Fig. 6 are presented in Table 5, which shows that the better-performing method in most cities is GAM.

Lastly, wind energy has been calculated for the real wind data and parameter estimation methods. Fig. 7 shows the comparison of the calculated values by all the methods. PD and GAM have shown the highest performance at calculating the power density closest to the actual value.

In conclusion, based on the wind data evaluation performed in this study, GAM emerged as the best performing approach for most regions. However, when calculating wind power, the PD method showed the lowest error value and was the closest to the actual wind data, as can be seen in Fig. 7. This finding is based on the ability of these methods to produce wind speed estimates that are closely aligned with actual wind data measurements, while at the same time exhibiting acceptable levels of error across the metrics evaluated.

B. LIFE-CYCLE ASSESSMENT

Table 8 presents the key environmental indicators used to conduct the LCA and resulting GWP, CED, and material emissions for each city. The regional variations highlight a clear trend: Çanakkale and Kırklareli, which benefit from the most consistent high-altitude wind resources, yielded the lowest GWP and CED values. This reinforces the significant advantage of deploying AWE systems in wind-rich coastal and near-coastal areas. Conversely, inland sites with lower average wind speeds, such as Aydın and Manisa, experienced higher per-kWh environmental impacts, showing the critical link between wind resource quality and the life-cycle performance of the technology.

Transportation emissions were highest for remote areas like Sinop, where proximity to major manufacturing hubs is limited. CFRP and Dyneema, while lightweight, showed consistent scaling advantages across all cities due to their low mass-to-strength ratio. Cities with cleaner electricity grids, such as İzmir, achieved lower GWP values due to reduced emissions during manufacturing and installation phases.

Fig. 8 illustrates the required material masses for AWE and HAWT plants, with foundations and towers dominating the HAWT's requirements. For AWE systems, the tether, landing apparatus, and ground station components contributed the most to the overall material demand, albeit at lower levels compared to HAWTs.

Fig. 9 provides a detailed breakdown of the material masses used in both systems, further highlighting the lower material requirements of AWE. Fig. 10 shows the weight of each material used in the AWE system, with larger amounts of materials generally contributing to a greater GWP. The findings revealed the advantages of AWE in material efficiency, reduced GWP, and lower CED than HAWTs due to optimized material use and access to higher-altitude winds.

Fig. 11 and Fig. 12 represent the calculated GWP and CED values, respectively, with the AWE system exhibiting approximately half the GWP and a lower CED compared to HAWT to generate 1 MWh of electricity.

The results for Global Warming Potential (GWP) are presented in kilograms of CO_2 equivalent per kilowatt-hour ($kgCO_2$-eq/kWh), while Cumulative Energy Demand (CED) is presented in megajoules per megawatt-hour (MJ/MWh). This approach is consistent with reporting practices in recent life cycle assessments of airborne wind energy systems [6], [44].

AWE Systems consumed significantly less steel and concrete compared to HAWTs due to the lightweight nature of airborne structures. Tether materials like Dyneema and CFRP exhibited higher embodied energy but contributed minimally to overall GWP due to their small mass relative to the system.

AWE systems demonstrated better recyclability due to their modular design and reliance on high value materials (e.g. CFRP), which have established recycling pathways. HAWTs showed higher environmental burdens in

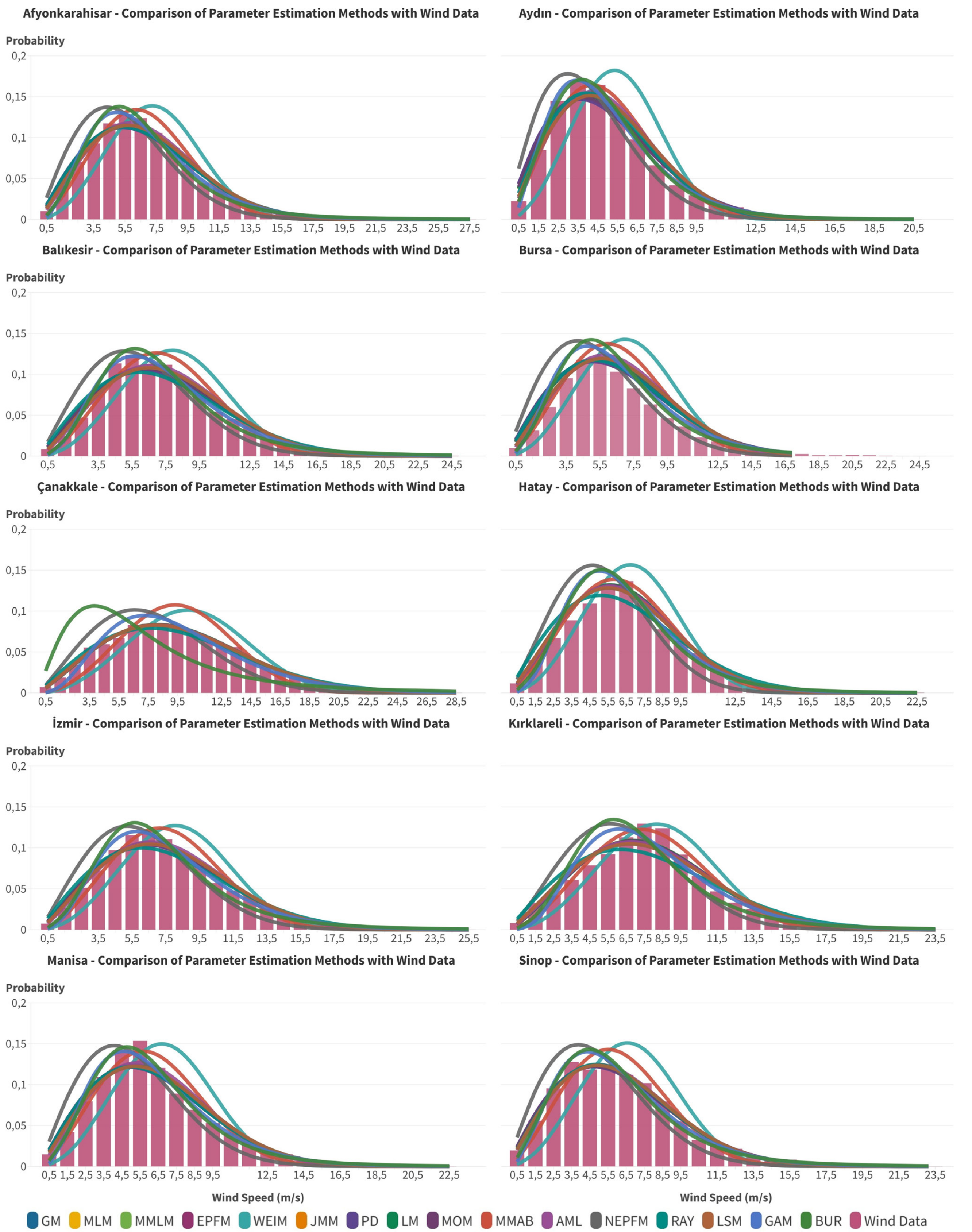

FIGURE 5. Comparative performance of parameter methods across case cities.

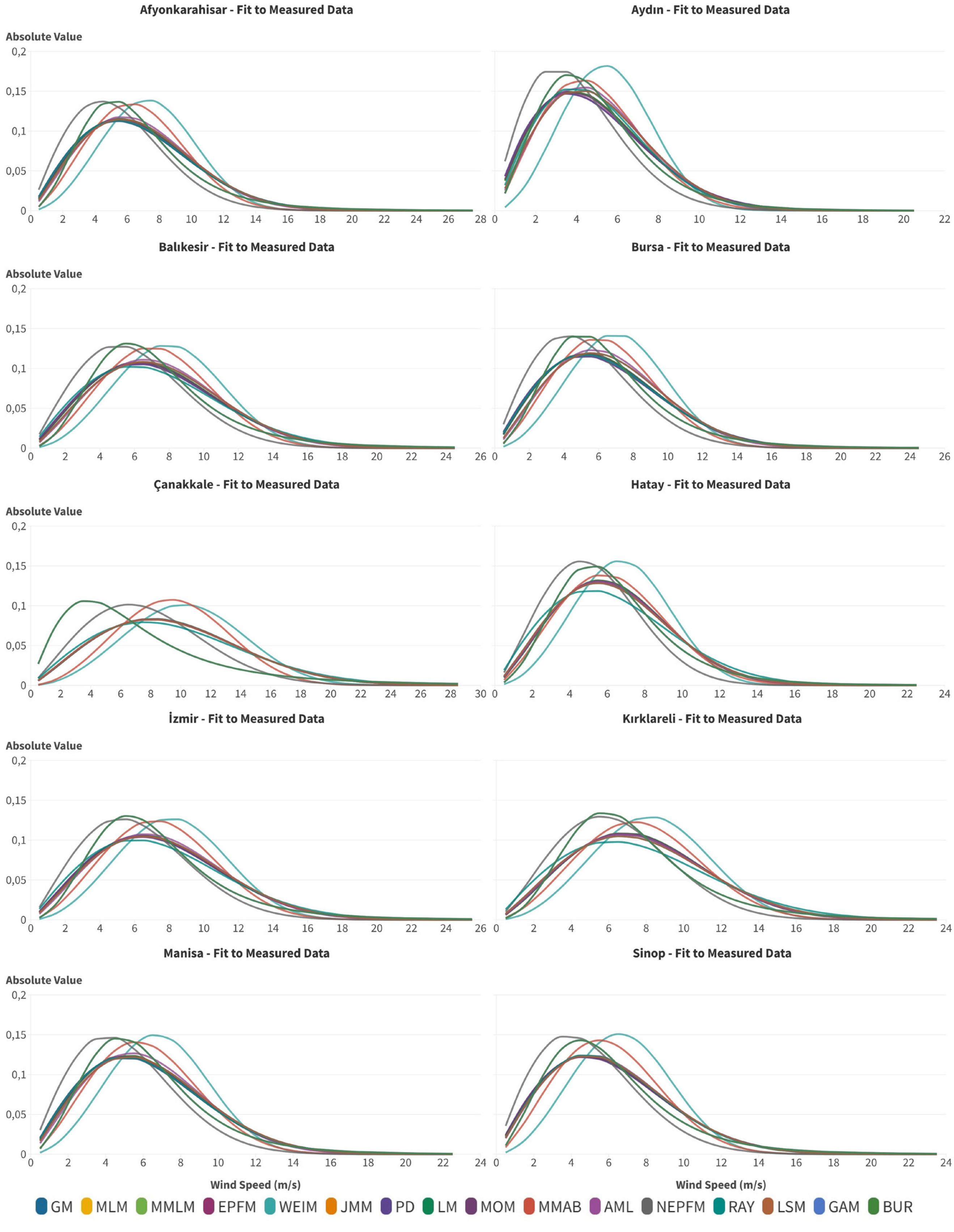

FIGURE 6. **Comparative accuracy analysis of estimation techniques across cities.**

TABLE 5. Number of data points closest to the actual wind data.

Afyonkarahisar		Aydın		Balıkesir		Bursa		Çanakkale	
Method	Nu. of Data Points	Method	Nu. of Data Points	Method	Nu. of Data Points	Method	Nu. of Data Points	Method	Nu. of Data Points
GAM	8	GAM	12	RAY	7	GAM	13	RAY	8
PD	6	PD	3	GAM	6	PD	6	MMLM	3
AML	6	MMAB	3	MMAB	3	AML	2	JMM	3
JMM	3	MMLM	1	AML	2	RAY	2	LM	3
WEIM	1	EPFM	1	GM	1	EPFM	1	WEIM	2
LM	1	AML	1	EPFM	1	WEIM	1	MMAB	2
MMAB	1	GM	0	JMM	1	GM	0	AML	2
NEPFM	1	MLM	0	PD	1	MLM	0	GM	1
LSM	1	WEIM	0	LM	1	MMLM	0	EPFM	1
GM	0	JMM	0	MOM	1	JMM	0	NEPFM	1
MLM	0	LM	0	NEPFM	1	LM	0	LSM	1
MMLM	0	MOM	0	MLM	0	MOM	0	GAM	1
EPFM	0	NEPFM	0	MMLM	0	MMAB	0	MLM	0
MOM	0	RAY	0	WEIM	0	NEPFM	0	PD	0
RAY	0	LSM	0	LSM	0	LSM	0	MOM	0
BUR	0	BUR	0	BUR	0	BUR	0	BUR	0
Hatay		İzmir		Kırklareli		Manisa		Sinop	
Method	Nu. of Data Points	Method	Nu. of Data Points	Method	Nu. of Data Points	Method	Nu. of Data Points	Method	Nu. of Data Points
MMAB	8	RAY	9	WEIM	5	GAM	10	PD	12
RAY	6	AML	4	GM	4	PD	4	GAM	5
GAM	3	GAM	4	RAY	4	AML	3	AML	4
GM	2	MMAB	3	MMAB	3	MMLM	2	RAY	2
LSM	2	PD	2	GAM	3	GM	1	EPFM	1
MMLM	1	GM	1	LSM	2	JMM	1	GM	0
MOM	0	MLM	1	MMLM	1	MMAB	1	MLM	0
MLM	0	MMLM	1	JMM	1	LSM	1	MMLM	0
EPFM	0	MOM	1	LM	1	MLM	0	WEIM	0
WEIM	0	EPFM	0	MLM	0	EPFM	0	JMM	0
JMM	0	WEIM	0	EPFM	0	WEIM	0	LM	0
PD	0	JMM	0	PD	0	LM	0	MOM	0
LM	0	LM	0	MOM	0	MOM	0	MMAB	0
AML	0	NEPFM	0	AML	0	NEPFM	0	NEPFM	0
NEPF	0	LSM	0	NEPFM	0	RAY	0	LSM	0
BUR	0	BUR	0	BUR	0	BUR	0	BUR	0

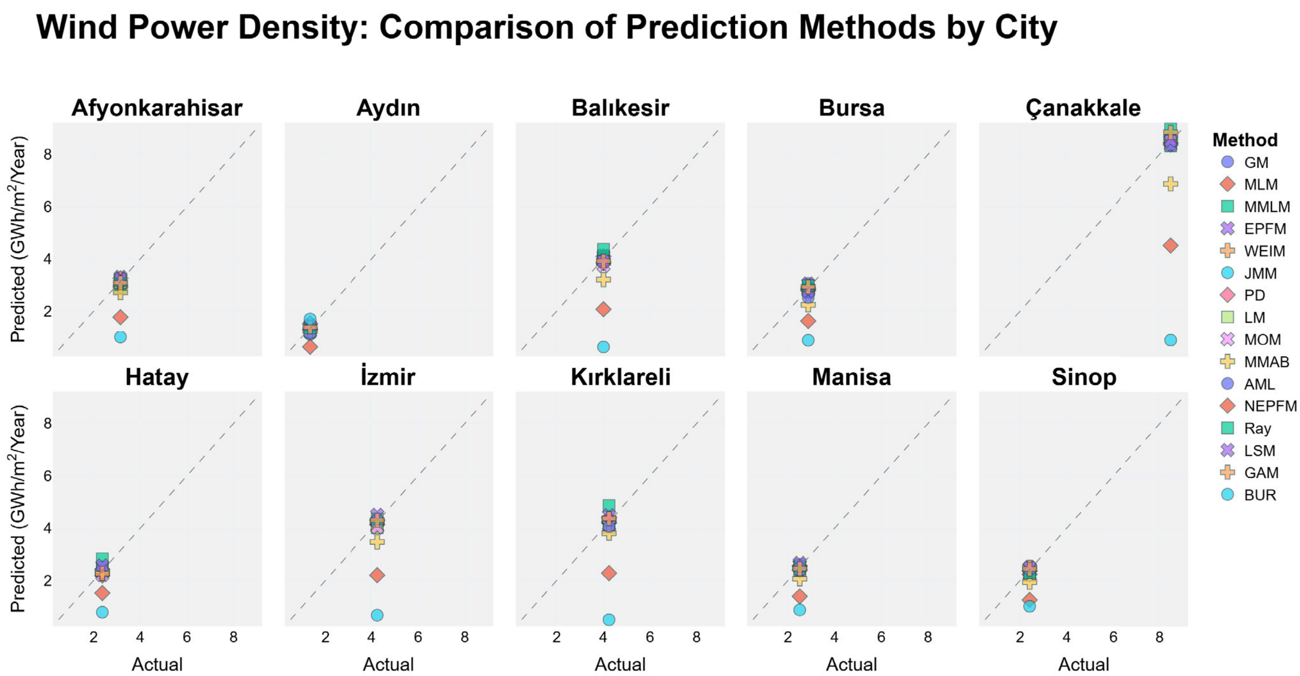

FIGURE 7. Wind power density comparison for each method.

decommissioning due to the large-scale disposal of concrete and steel components.

The findings reveal that AWE systems offer notable environmental advantages over HAWTs, particularly in GWP and CED. The reduced use of bulk materials such as steel and concrete in AWE systems not only reduces the carbon footprint but also improves their adaptability to deployment in remote or challenging terrains. However, the reliance

TABLE 6. Evaluation of estimation methods using performance metrics for each city.

	Afyonkarahisar				Aydin				Balikesir				Bursa				Canakkale			
	WEE	RMSE	R^2	χ^2	WEE	RMSE	R^2	χ^2	WEE	RMSE	R^2	χ^2	WEE	RMSE	R^2	χ^2	WEE	RMSE	R^2	χ^2
GM	4.7E-3	0.13	0.998	6.0E-5	1.3E-2	0.17	0.993	1.3E-4	3.9E-3	0.15	0.996	1.1E-4	3.1E-3	0.17	0.993	1.8E-4	3.0E-3	0.05	0.999	1.4E-6
MLM	2.9E-2	0.11	0.999	3.5E-5	4.0E-2	0.13	0.997	4.6E-5	2.0E-2	0.12	0.998	5.5E-5	3.3E-2	0.14	0.998	8.5E-5	3.1E-4	0.05	0.999	1.2E-6
MMLM	2.3E-2	0.12	0.998	3.7E-5	2.9E-2	0.13	0.997	4.9E-5	1.4E-2	0.13	0.998	5.8E-5	2.7E-2	0.14	0.997	8.8E-5	4.2E-3	0.05	0.999	1.4E-6
EPFM	5.8E-3	0.13	0.998	5.2E-5	4.6E-3	0.14	0.997	5.7E-5	5.3E-3	0.13	0.998	6.2E-5	5.7E-3	0.15	0.996	1.0E-4	4.7E-3	0.05	0.999	1.4E-6
WEIM	8.5E-3	0.28	0.950	1.3E-3	2.2E-2	0.30	0.930	1.4E-3	1.4E-3	0.27	0.954	1.3E-3	1.1E-2	0.29	0.942	1.5E-3	1.0E-3	0.27	0.956	1.6E-3
JUS	3.9E-2	0.11	0.999	2.9E-5	4.4E-2	0.13	0.998	4.4E-5	3.0E-2	0.12	0.998	5.0E-5	4.1E-2	0.14	0.997	8.0E-5	9.0E-3	0.05	0.999	2.0E-6
PD	8.9E-9	0.13	0.998	5.7E-5	2.4E-7	0.14	0.997	6.0E-5	3.5E-10	0.13	0.998	6.6E-5	1.8E-12	0.15	0.996	1.1E-4	9.6E-9	0.05	0.999	1.2E-6
LYS	3.7E-2	0.11	0.999	3.0E-5	4.2E-2	0.13	0.998	4.4E-5	2.8E-2	0.12	0.998	5.1E-5	4.0E-2	0.14	0.997	8.1E-5	7.7E-3	0.05	0.999	2.1E-6
MOM	2.9E-2	0.11	0.999	3.5E-5	3.1E-2	0.13	0.998	4.7E-5	2.1E-2	0.12	0.998	5.3E-5	3.1E-2	0.14	0.997	8.5E-5	2.5E-4	0.05	0.999	1.2E-6
MMAB	1.9E-1	0.16	0.994	1.4E-4	1.6E-1	0.15	0.996	8.7E-5	1.7E-1	0.17	0.993	2.1E-4	1.9E-1	0.17	0.992	2.0E-4	2.1E-1	0.22	0.979	7.4E-4
AML	4.4E-2	0.12	0.998	4.6E-5	6.6E-2	0.16	0.994	1.1E-4	3.3E-2	0.14	0.997	9.8E-5	5.3E-2	0.17	0.994	1.6E-4	7.9E-4	0.05	0.999	1.3E-6
NEPFM	4.5E-1	0.30	0.936	1.6E-3	4.4E-1	0.27	0.952	9.5E-4	4.5E-1	0.30	0.937	1.8E-3	4.5E-1	0.29	0.943	1.5E-3	4.5E-1	0.31	0.918	2.9E-3
RAY	6.5E-3	0.12	0.998	5.1E-5	8.6E-2	0.13	0.998	4.2E-5	4.3E-2	0.15	0.996	1.1E-4	2.1E-2	0.14	0.997	9.0E-5	6.6E-2	0.11	0.999	3.9E-5
LSM	4.7E-3	0.13	0.998	6.0E-5	1.3E-2	0.17	0.993	1.3E-4	3.9E-3	0.15	0.996	1.1E-4	3.1E-3	0.17	0.993	1.8E-4	3.0E-3	0.05	0.999	1.4E-6
GAM	6.8E-4	0.10	0.998	3.8E-5	1.6E-4	0.06	0.999	4.7E-6	7.6E-3	0.07	0.999	1.6E-5	1.0E-3	0.08	0.999	1.4E-5	2.9E-2	0.13	0.997	9.4E-5
BUR	7.3E-1	0.12	0.998	4.6E-5	1.7E-1	0.05	0.999	1.5E-6	8.3E-1	0.12	0.999	4.2E-5	6.8E-1	0.07	0.999	5.1E-6	9.0E-1	0.38	0.828	6.0E-3

	Hatay				Izmir				Kirklareli				Manisa				Sinop			
	WEE	RMSE	R^2	χ^2	WEE	RMSE	R^2	χ^2	WEE	RMSE	R^2	χ^2	WEE	RMSE	R^2	χ^2	WEE	RMSE	R^2	χ^2
GM	1,4E-2	0,11	0,999	2,5E-5	1,6E-2	0,13	0,998	6,4E-5	3,1E-2	0,14	0,997	9,5E-5	1,8E-2	0,15	0,996	1,1E-4	9,5E-3	0,10	0,999	1,8E-5
MLM	5,8E-3	0,10	0,999	1,5E-5	1,4E-2	0,11	0,999	3,6E-5	5,5E-3	0,13	0,998	6,4E-5	2,5E-2	0,13	0,998	6,2E-5	1,3E-2	0,08	0,999	9,9E-6
MMLM	7,2E-4	0,10	0,999	1,7E-5	8,5E-3	0,11	0,999	3,9E-5	1,4E-3	0,13	0,998	6,9E-5	1,7E-2	0,14	0,997	6,6E-5	1,0E-2	0,08	0,999	1,0E-5
EPFM	2,2E-3	0,10	0,999	1,5E-5	4,9E-3	0,11	0,999	3,9E-5	1,9E-3	0,13	0,998	6,5E-5	5,8E-3	0,14	0,997	7,1E-5	5,6E-3	0,09	0,999	1,1E-5
WEIM	6,0E-3	0,24	0,974	6,1E-4	2,0E-4	0,27	0,956	1,3E-3	6,3E-3	0,24	0,975	7,6E-4	7,9E-3	0,29	0,946	1,3E-3	1,1E-2	0,29	0,941	1,4E-3
JUS	1,5E-2	0,09	0,999	9,9E-6	2,3E-2	0,11	0,999	3,4E-5	1,5E-2	0,12	0,998	5,3E-5	3,4E-2	0,13	0,998	5,9E-5	2,3E-2	0,08	0,999	8,8E-6
PD	8,3E-7	0,10	0,999	1,6E-5	3,1E-9	0,12	0,998	4,2E-5	2,4E-12	0,13	0,998	6,7E-5	6,4E-9	0,14	0,997	7,5E-5	1,2E-10	0,09	0,999	1,2E-5
LYS	1,5E-2	0,09	0,999	9,9E-6	2,2E-2	0,11	0,998	3,4E-5	1,5E-2	0,12	0,998	5,4E-5	3,3E-2	0,13	0,998	5,9E-5	2,1E-2	0,08	0,999	9,1E-6
MOM	8,9E-3	0,09	0,999	1,2E-5	1,5E-2	0,11	0,998	3,6E-5	9,2E-3	0,13	0,998	5,8E-5	2,4E-2	0,13	0,997	6,2E-5	1,1E-2	0,08	0,999	1,0E-5
MMAB	6,5E-2	0,09	0,999	1,4E-5	1,6E-1	0,18	0,992	2,3E-4	1,1E-1	0,14	0,997	8,1E-5	1,6E-1	0,16	0,994	1,5E-4	1,8E-1	0,18	0,992	1,9E-4
AML	5,6E-3	0,09	0,999	1,5E-5	2,4E-2	0,12	0,998	5,4E-5	4,7E-3	0,13	0,998	6,6E-5	3,9E-2	0,15	0,996	8,7E-5	2,5E-2	0,10	0,999	1,7E-5
NEPFM	4,2E-1	0,31	0,932	1,6E-3	4,4E-1	0,299	0,934	1,9E-3	4,3E-1	0,31	0,930	2,1E-3	4,5E-1	0,29	0,943	1,4E-3	4,5E-1	0,29	0,941	1,4E-3
RAY	1,2E-1	0,17	0,994	1,4E-4	5,7E-2	0,14	0,997	9,1E-5	1,3E-1	0,19	0,991	2,7E-4	5,9E-3	0,14	0,997	7,1E-5	3,5E-2	0,08	0,999	8,9E-6
LSM	1,4E-2	0,11	0,999	2,5E-5	1,6E-2	0,13	0,998	6,4E-5	3,1E-2	0,14	0,997	9,5E-5	1,8E-2	0,15	0,996	1,1E-4	9,5E-3	0,10	0,999	1,8E-5
GAM	1,8E-2	0,14	0,996	1,0E-4	1,4E-2	0,09	0,999	2,7E-5	1,8E-2	0,14	0,995	1,62-4	6,0E-3	0,09	0,999	2,3E-5	2,0E-2	0,11	0,999	3,3E-5
BUR	6,1E-1	0,15	0,996	8,5E-5	8,4E-1	0,16	0,995	1,5E-4	8,4E-1	0,21	0,984	4,7E-4	5,9E-1	0,09	0,999	1,1E-5	5,6E-1	0,12	0,998	4,8E-5

TABLE 7. Ranking based on error values for each method for every city.

	Afyonkarahisar				Aydin				Balikesir				Bursa				Canakkale			
Rank	WEE	RMSE	R^2	χ^2	WEE	RMSE	R^2	χ^2	WEE	RMSE	R^2	χ^2	WEE	RMSE	R^2	χ^2	WEE	RMSE	R^2	χ^2
1	PD	GAM	JUS	JUS	PD	BUR	BUR	BUR	PD	GAM	GAM	NEPFM	PD	BUR	BUR	BUR	PD	MOM	MOM	MOM
2	GAM	JUS	LYS	LYS	GAM	GAM	GAM	GAM	WEIM	BUR	BUR	WEIM	GAM	GAM	GAM	GAM	MOM	PD	PD	PD
3	LSM	LYS	MLM	MLM	EPFM	RAY	RAY	RAY	GM	JUS	JUS	MMAB	LSM	JUS	JUS	JUS	MLM	MLM	MLM	MLM
4	GM	MLM	MOM	MOM	LSM	JUS	JUS	JUS	LSM	LYS	LYS	LSM	GM	LYS	LYS	LYS	AML	AML	AML	AML
5	EPFM	MOM	MMLM	MMLM	GM	LYS	LYS	LYS	EPFM	MOM	MOM	GM	EPFM	MOM	MOM	MOM	WEIM	GM	GM	GM
6	RAY	MMLM	GAM	GAM	WEIM	MLM	MLM	MLM	GAM	MLM	MLM	RAY	WEIM	MLM	MLM	MLM	GM	LSM	LSM	LSM
7	WEIM	AML	AML	AML	MMLM	MOM	MOM	MOM	MMLM	MMLM	MMLM	AML	RAY	MMLM	MMLM	MMLM	LSM	EPFM	EPFM	EPFM
8	MMLM	BUR	BUR	BUR	MOM	MMLM	MMLM	MMLM	MLM	EPFM	EPFM	PD	MMLM	RAY	RAY	RAY	MMLM	MMLM	MMLM	MMLM
9	MLM	RAY	RAY	RAY	MLM	EPFM	EPFM	EPFM	MOM	PD	PD	EPFM	MOM	EPFM	EPFM	EPFM	EPFM	JUS	JUS	JUS
10	MOM	EPFM	EPFM	EPFM	LYS	PD	PD	PD	LYS	AML	AML	MMLM	MLM	PD	PD	PD	LYS	LYS	LYS	LYS
11	LYS	PD	PD	PD	JUS	MMAB	MMAB	MMAB	JUS	RAY	RAY	MLM	LYS	AML	AML	AML	JUS	RAY	RAY	RAY
12	JUS	GM	GM	GM	AML	AML	AML	AML	AML	GM	GM	MOM	JUS	GM	GM	GM	GAM	GAM	GAM	GAM
13	AML	LSM	LSM	LSM	RAY	GM	GM	GM	RAY	LSM	LSM	LYS	AML	LSM	LSM	LSM	RAY	MMAB	MMAB	MMAB
14	MMAB	MMAB	MMAB	MMAB	MMAB	LSM	LSM	LSM	MMAB	MMAB	MMAB	JUS	MMAB	MMAB	MMAB	MMAB	MMAB	WEIM	WEIM	WEIM
15	NEPFM	WEIM	WEIM	WEIM	BUR	NEPFM	NEPFM	NEPFM	NEPFM	WEIM	WEIM	BUR	NEPFM	NEPFM	NEPFM	NEPFM	NEPFM	NEPFM	NEPFM	NEPFM
16	BUR	NEPFM	NEPFM	NEPFM	NEPFM	WEIM	WEIM	WEIM	BUR	NEPFM	NEPFM	GAM	BUR	WEIM	WEIM	BUR	BUR	BUR	BUR	

	Hatay				Izmir				Kirklareli				Manisa				Sinop			
Rank	WEE	RMSE	R^2	χ^2	WEE	RMSE	R^2	χ^2	WEE	RMSE	R^2	χ^2	WEE	RMSE	R^2	χ^2	WEE	RMSE	R^2	χ^2
1	PD	JUS	JUS	JUS	PD	GAM	GAM	GAM	PD	JUS	JUS	JUS	PD	GAM	BUR	BUR	PD	JUS	JUS	JUS
2	MMLM	LYS	LYS	LYS	WEIM	JUS	JUS	JUS	MMLM	LYS	LYS	LYS	EPFM	BUR	GAM	GAM	EPFM	RAY	RAY	RAY
3	EPFM	MOM	MOM	MOM	EPFM	LYS	LYS	LYS	EPFM	MOM	MOM	MOM	RAY	JUS	JUS	JUS	LSM	LYS	LYS	LYS
4	AML	MMAB	MMAB	MMAB	MMLM	MOM	MOM	MOM	AML	MLM	MLM	MLM	GAM	LYS	LYS	LYS	GM	MLM	MLM	MLM
5	MLM	MLM	MLM	MLM	MLM	MLM	MLM	MLM	MLM	EPFM	EPFM	EPFM	WEIM	MOM	MOM	MOM	MMLM	MOM	MOM	MOM
6	WEIM	AML	AML	AML	GAM	MMLM	MMLM	MMLM	WEIM	AML	AML	AML	MMLM	MLM	MLM	MLM	MOM	MMLM	MMLM	MMLM
7	MOM	EPFM	EPFM	EPFM	MOM	EPFM	EPFM	EPFM	MOM	PD	PD	PD	GM	MMLM	MMLM	MMLM	WEIM	EPFM	EPFM	EPFM
8	GM	PD	PD	PD	GM	PD	PD	PD	LYS	MMLM	MMLM	MMLM	LSM	RAY	RAY	RAY	MLM	PD	PD	PD
9	LSM	MMLM	MMLM	MMLM	LSM	AML	AML	AML	JUS	MMAB	MMAB	MMAB	MOM	EPFM	EPFM	EPFM	GAM	AML	AML	AML
10	LYS	GM	GM	GM	LYS	GM	GM	GM	GAM	GAM	GM	GM	MLM	PD	PD	PD	LYS	GM	GM	GM
11	JUS	LSM	LSM	LSM	JUS	LSM	LSM	LSM	GM	GM	LSM	LSM	LYS	AML	AML	AML	JUS	LSM	LSM	LSM
12	GAM	GAM	BUR	BUR	AML	RAY	RAY	RAY	LSM	LSM	GAM	GAM	JUS	GM	GM	GM	AML	GAM	GAM	GAM
13	MMAB	BUR	GAM	GAM	RAY	BUR	BUR	BUR	MMAB	RAY	RAY	RAY	AML	LSM	LSM	LSM	RAY	BUR	BUR	BUR
14	RAY	RAY	RAY	RAY	MMAB	MMAB	MMAB	MMAB	RAY	BUR	BUR	BUR	MMAB	MMAB	MMAB	MMAB	MMAB	MMAB	MMAB	MMAB
15	NEPFM	WEIM	WEIM	WEIM	NEPFM	WEIM	WEIM	WEIM	NEPFM	WEIM	WEIM	WEIM	NEPFM	WEIM	WEIM	WEIM	NEPFM	WEIM	WEIM	WEIM
16	BUR	NEPFM	NEPFM	NEPFM	BUR	NEPFM	NEPFM	NEPFM	BUR	NEPFM	NEPFM	NEPFM	BUR	NEPFM	NEPFM	NEPFM	BUR	NEPFM	NEPFM	NEPFM

on high-performance materials like CFRP and Dyneema highlights the importance of efficient recycling technologies to mitigate their embodied energy.

A key observation is the role of operational efficiency in shaping environmental performance. AWE systems, operating at higher altitudes with more consistent wind speeds, demonstrated superior capacity factors, further amplifying their environmental benefits per kWh basis. In contrast, HAWTs in similar regions required higher material inputs to achieve comparable energy output, underscoring the intrinsic efficiency of AWE technology.

Despite these advantages, the study identified areas for improvement in AWE systems:

1) Material Optimization: Reducing the reliance on high-embodied-energy materials like CFRP through innovative designs or alternative materials.
2) Recycling Pathways: Enhancing recycling and reuse mechanisms for tether and kite components to further minimize environmental impacts.
3) Scalability Challenges: Addressing logistical and manufacturing challenges associated with scaling AWE systems to larger capacities.

TABLE 8. Key environmental indicators.

	Performance		Life Cycle Assessment		
	Wind Speed (m/s)	Capacity Factor	GWP ($kgCO_2$-eq /kwh)	CED (MJ/ kwh)	Material Emiss. ($kgCO_2$-eq /kwh)
Afyonkarahisar	6.7	0.23	0.0079	0.074	0.015
Aydın	4.9	0.11	0.0074	0.069	0.011
Balıkesir	7.4	0.32	0.0076	0.072	0.009
Bursa	6.5	0.21	0.0077	0.072	0.014
Çanakkale	9.6	0.48	0.0074	0.070	0.010
Hatay	6.4	0.20	0.0079	0.073	0.012
İzmir	7.6	0.33	0.0072	0.068	0.008
Kırklareli	7.8	0.39	0.0075	0.070	0.017
Manisa	6.2	0.19	0.0075	0.071	0.013
Sinop	6.1	0.20	0.0073	0.067	0.016

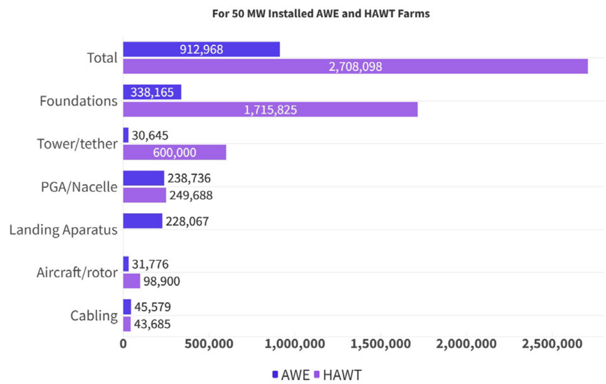

FIGURE 8. The Masses of AWE and HAWT systems.

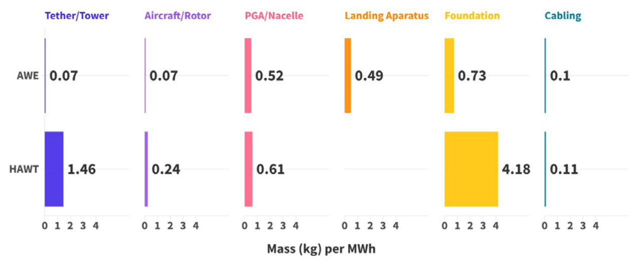

FIGURE 9. Masses of AWE and HAWT based on the produced MWh.

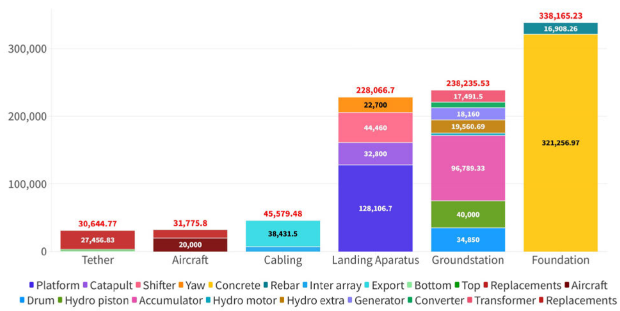

FIGURE 10. Masses of the AWE system per each sub-material [kg].

The LCA results underscore the environmental superiority of AWE systems compared to HAWTs, highlighting their potential as a sustainable and scalable renewable energy solution. By utilizing lightweight materials and high-altitude wind resources, AWE systems achieve lower environmental impacts while maintaining competitive energy outputs. These findings provide valuable insights for the optimization and broader adoption of AWE technology, contributing to global renewable energy goals.

C. TECHNO-ECONOMIC ASSESSMENT

To contextualize the findings, it is useful to directly compare the reference AWE system with a conventional HAWT and to consider the broader factors influencing deployment. Table 9 provides a summary comparison. The primary advantages of the AWE system appear to be its access to higher-altitude winds, which can lead to higher capacity factors, and its dramatically lower material mass.

Of course, these potential benefits must be balanced against significant challenges, particularly regarding operational reliability. AWE remains an emerging technology, with well-documented issues such as component fatigue; tether degradation being a typical example, and ensuring continuous safe operation in adverse weather conditions [7], [45]. Achieving full commercial maturity will largely depend on overcoming these limitations. Current research is increasingly adapting methodologies from aerospace engineering, such as Failure Mode and Effects Analysis (FMEA), to enhance dependability [13].

Although this study does not provide a detailed failure rate analysis, practical considerations were incorporated into the techno-economic model. As illustrated in Fig. 16, a substantial fraction of the lifetime operational expenditure (OPEX) is attributed to *Replacements* and *Transport of Operation & Maintenance*. These categories effectively capture costs associated with tether exchange, electrical component replacement, and general servicing, thereby internalizing expected downtime and wear-and-tear. While this approach introduces a degree of realism into the economic projections, it must be emphasized that reliability remains a major source of uncertainty for technologies that have yet to achieve full-scale commercialization.

The TEA results are shown in both Tables 10 and 11, one of them presenting TEA assessment for each city, while the other presents results as NPV, LCOE, and payback period for each city.

The techno-economic analysis, grounded in the dynamically calculated, location-specific capacity factors, reveals a much more nuanced picture of AWE's economic viability across Türkiye. The results, summarized in Table 11, show a wide divergence in performance that is clearly and directly linked to the quality of the wind resources presented in Table 10.

In regions with excellent high-altitude winds, the economic case for AWE appears quite strong. Çanakkale, with the highest average wind speed of 9.6 m/s, emerges as the top-performing location. It boasts a projected Levelized Cost of Electricity (LCOE) of just \$0.0420/kWh, a very high Internal Rate of Return (IRR) of 18.71%, and a payback

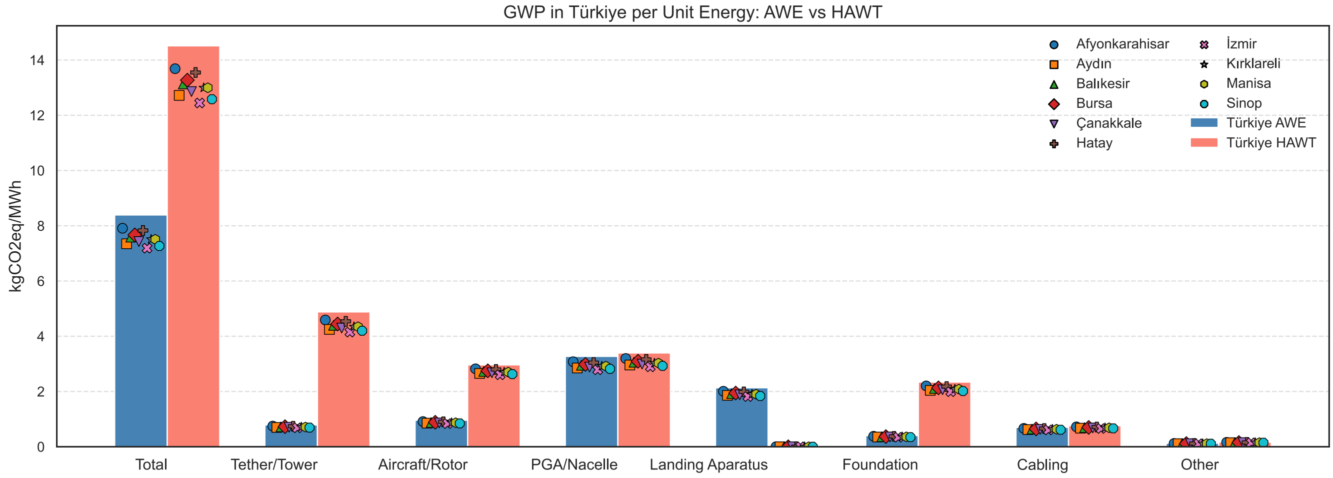

FIGURE 11. Comparison of global warming potential for AWE and HAWT systems across all cities.

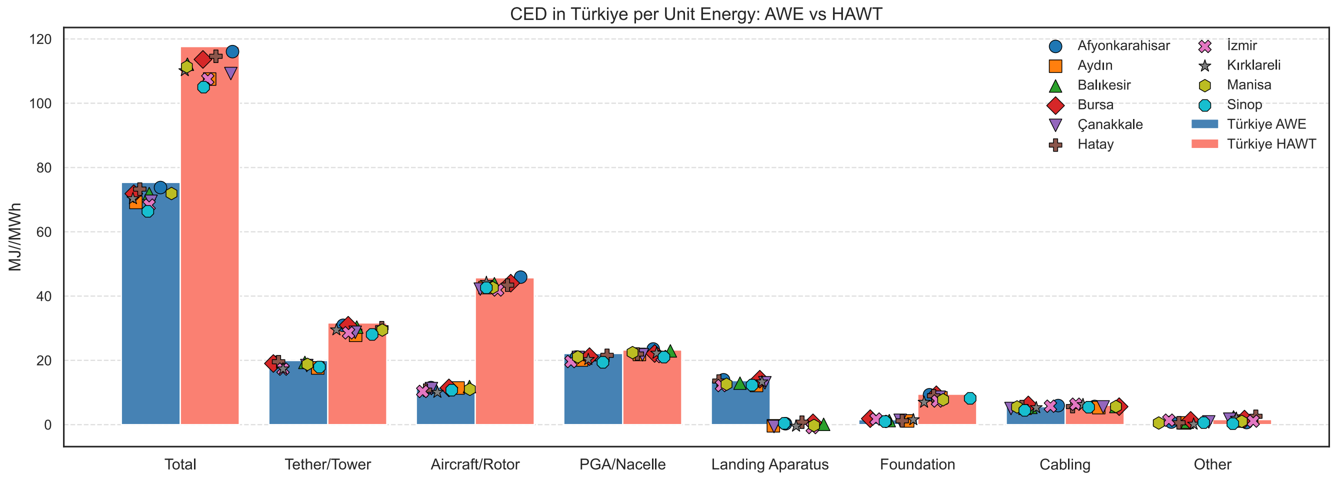

FIGURE 12. Comparison of cumulative energy demand for AWE and HAWT systems across all cities.

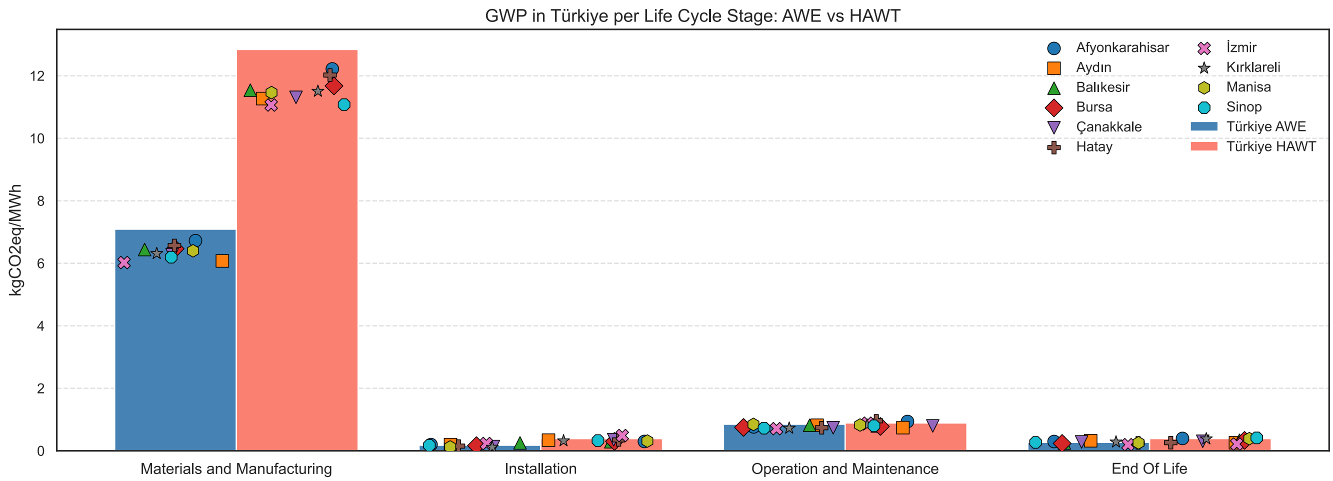

FIGURE 13. Global warming potential per life cycle stage.

period of just over six years. Similarly, Kırklareli (7.8 m/s) and İzmir (7.6 m/s) show compelling results, with LCOEs of \$0.0462/kWh and \$0.0548/kWh, respectively, and healthy positive Net Present Values (NPVs). These figures suggest that in prime coastal locations, AWE could be highly competitive with other new-build renewable sources.

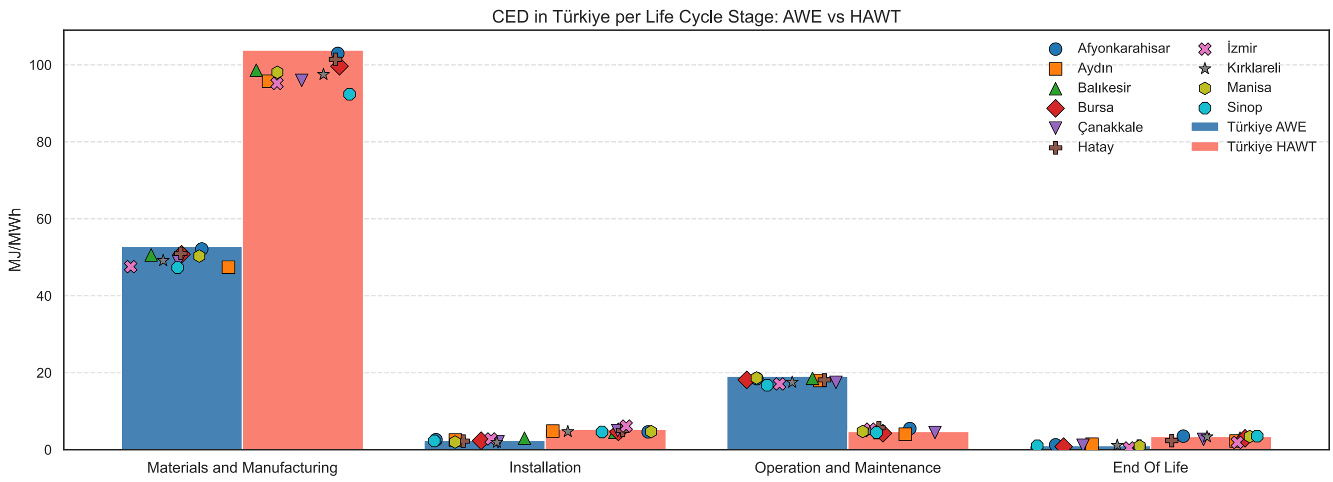

FIGURE 14. Cumulative energy demand per life cycle stage.

TABLE 9. Comparative summary of AWE and HAWT systems.

Feature	AWE System (This Study)	HAWT (Typical)	Key Difference/Advantage
Rated Power	5.0 MW	5.0 MW	Baseline for comparison
TRL	6-7	9	Maturity and bankability
Operating Altitude	200–500 m	∼80–100 m	Access to stronger, more consistent winds
Key Materials	CFRP, Dyneema, Steel	Steel, Concrete, GFRP	AWE has significantly lower mass
Land Footprint	Potentially smaller ground station	Larger foundation and exclusion zone	AWE offers deployment flexibility
Capacity Factor	0.28–0.40 (Calculated)	0.25–0.35 (Typical for region)	Higher potential due to altitude
Lifespan	20 years	20–25 years	Comparable project lifetime

TABLE 10. City-wise techno-economic assessment.

City	Capacity Factor	CAPEX ($)	OPEX ($)	Wind Speed (m/s)	Discount Rate	Energy Price ($/MWh)	Project Life (Years)
Afyonkarahisar	0.23	1,500,124.81	11,935.23	6.73	0.095	72	20
Aydın	0.11	1,500,124.81	16,582.03	4.93	0.08	72	20
Balıkesir	0.32	1,616,684.01	16,459.76	7.16	0.09	73	20
Bursa	0.21	1,665,832.37	17,306.75	6.50	0.09	73	20
Çanakkale	0.48	1,698,335.05	17,667.52	9.59	0.085	74	20
Hatay	0.20	1,615,900.07	16,980.75	6.38	0.09	73	20
İzmir	0.33	1,578,390.94	16,585.20	7.79	0.08	75	20
Kırklareli	0.39	1,557,770.20	16,217.86	7.76	0.09	75	20
Manisa	0.19	1,615,063.45	16,980.75	6.45	0.09	75	20
Sinop	0.20	1,663,695.47	17,386.02	6.10	0.085	74	20

However, the analysis also underscores the critical importance of site selection. In contrast to the coastal frontrunners, several locations with more moderate or poor wind resources present a challenging business case. The results for Aydın are particularly telling; its low average wind speed of 4.9 m/s (which is very close to the system's cut-in speed) logically results in a very low capacity factor. This, in turn, leads to an unviable LCOE of $0.1640/kWh and a deeply negative NPV, making it an unsuitable site. Other cities with moderate wind speeds, such as Bursa, Hatay, Manisa, and Sinop, also show negative NPVs, suggesting that under the current cost and revenue assumptions, AWE deployment would not be economically feasible in these specific areas without additional policy support or technological improvements.

A detailed breakdown of the project's cost composition is important for understanding its economic drivers. Figs. 15 and 16 provide this granular analysis for the Capital Expenditure (CAPEX) and Operational Expenditure (OPEX), respectively, detailing the costs for each component and sub-classification across all ten cities.

As shown in Fig. 15, the CAPEX is primarily driven by the costs associated with the Foundations and the Power Generation Apparatus (PGA), with costs for foundations alone exceeding 600k Turkish Lira in some locations. The Aircraft and the Platform (LLA) represent the next significant cost blocks. In contrast, Fig. 16 details the lifetime OPEX, where the costs are dominated by Transport of Operation & Maintenance and component Replacements. The data shows

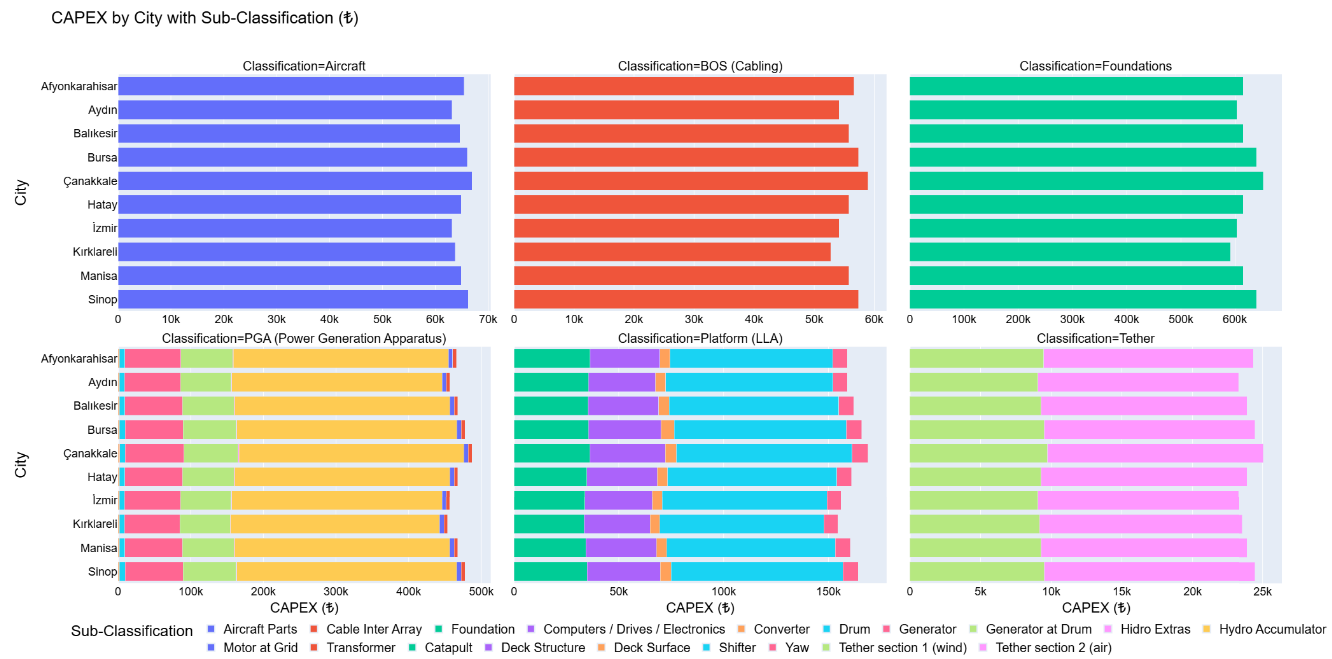

FIGURE 15. All the parts of the AWE plant and their effects on CAPEX for each city.

TABLE 11. City-wise techno-economic results.

City	NPV ($)	LCOE ($/kWh)	IRR (%)	Payback Period
Afyonkarahisar	-183,683	0.081	7.70	11 Years, 1 Month
Aydın	-883,799	0.164	-1.64	Not Achieved
Balıkesir	187,652	0.065	11.13	8 Years, 11 Months
Bursa	-443,048	0.097	5.02	13 Years, 5 Months
Çanakkale	1,409,108	0.042	18.71	6 Years, 2 Months
Hatay	-419,330	0.101	5.55	12 Years, 11 Months
İzmir	634,335	0.055	13.05	8 Years, 0 Months
Kırklareli	1,023,700	0.046	16.01	6 Years, 11 Months
Manisa	-479,333	0.103	4.52	14 Years
Sinop	-495,309	0.101	4.51	14 Years

that routine maintenance and the scheduled replacement of parts like the tether and electrical components constitute the vast majority of the operational budget, while consumables and disassembly activities are minor in comparison. These figures provide the detailed cost breakdown and confirm that the overall cost structure is largely consistent across the different regions studied.

These figures offer the detailed cost composition requested and confirm that while there are minor variations between locations, the overall cost structure of the AWE system is consistent across the regions studied.

It is worth seeing how these findings stack up against similar assessments of AWE in other parts of the world. Our projected LCOE for Türkiye's most promising coastal sites, which falls in the range of $0.042/kWh$ to $0.055/kWh$, appears to be highly competitive. For instance, a recent techno-economic review found that LCOE projections for AWE systems generally fall between €x20AC;0.033/kWh and €x20AC;0.059/kWh [46]. On the environmental side, our finding of a GWP as low as 7.2 gCO_2-eq/kWh also falls in close range with similar studies, where around 7.8 gCO_2-eq/kWh is calculated [6]. This comparison suggests that the potential for AWE in Türkiye is not just a local opportunity, but is competitive on a global scale.

The analysis also reveals a clear and important distinction between the performance of coastal and inland locations. The superior economic viability of cities like Çanakkale, Kırklareli, and İzmir is a direct result of their better wind resources. Their access to stronger, more consistent winds translates into significantly higher capacity factors, which is the dominant driver of their favorable LCOE and NPV values.

Beyond the wind itself, however, our model also sought to capture the logistical realities of these different locations. The city-specific cost breakdowns shown earlier in Figs. 15 and 16 reflect this, with variations in both CAPEX and OPEX components across the sites. For instance, the costs associated with "Foundations" and "Transport of Operation & Maintenance" are not uniform; they are influenced by factors like proximity to major ports and industrial centers where materials and specialized labor are sourced. While the wind quality is clearly the main character in this economic story, these logistical considerations play a supporting role, often giving coastal cities an additional, subtle advantage over more remote, inland sites like Afyonkarahisar.

D. SENSITIVITY AND UNCERTAINTY ANALYSIS

To address the potential impact of uncertainties in the economic assumptions, a sensitivity analysis was conducted.

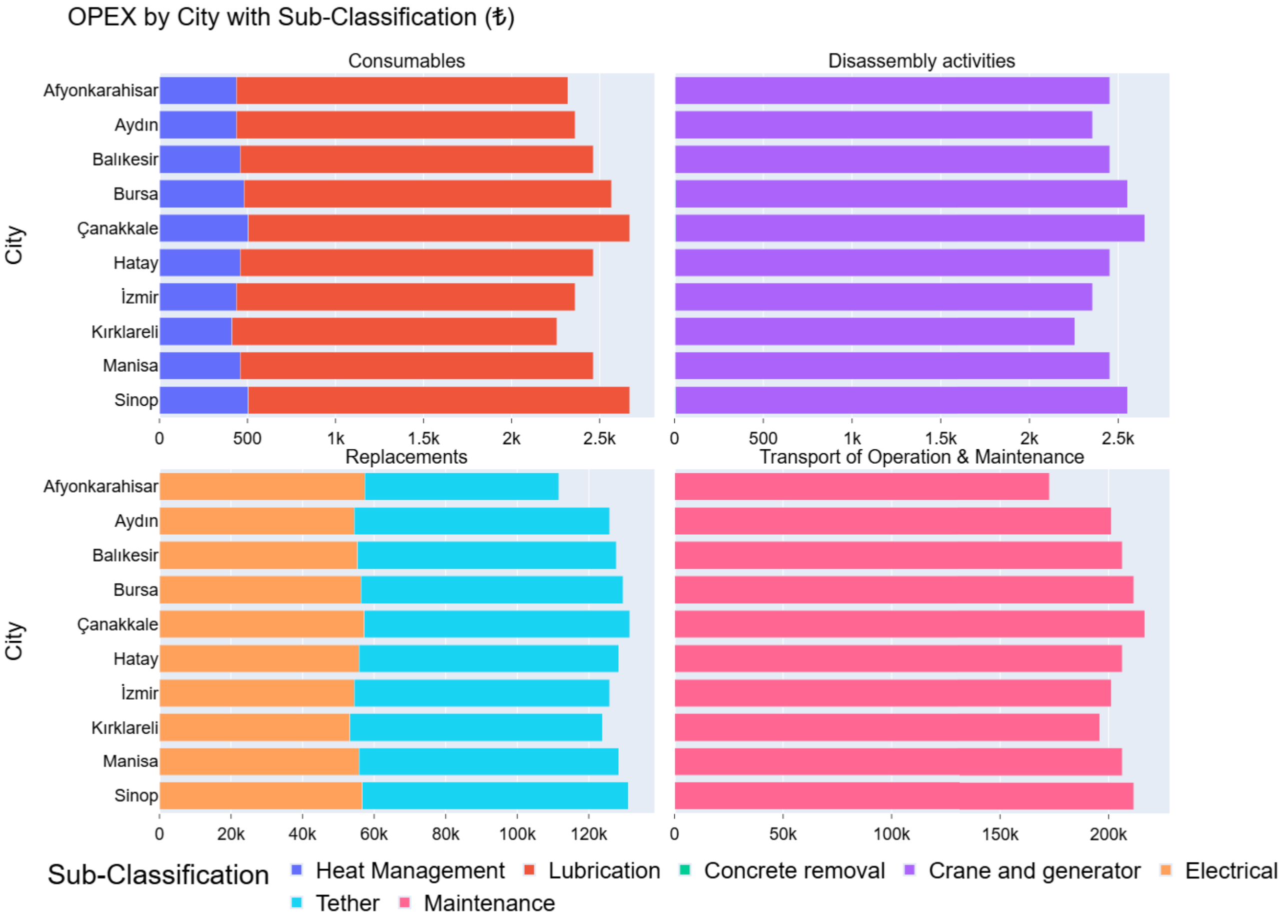

FIGURE 16. Operational expenses of AWE plant for Each City.

This analysis helps to identify which financial parameters have the most significant influence on the project's viability. For this purpose, İzmir was selected as a representative site, given its favorable techno-economic outlook in the baseline scenario. This single-site analysis is considered representative because while the absolute economic outcomes vary by location, the relative sensitivity of the project's finances to these key inputs is driven by the underlying economic model and is therefore consistent across all regions.

The analysis involved systematically varying four key input parameters; Capital Expenditure (CAPEX), Discount Rate, Operational Expenditure (OPEX), and Energy Price by ±20% from their initial values, while holding all other variables constant. The resulting effect on the Levelized Cost of Electricity (LCOE) was recorded and is visualized in the tornado plot presented in Fig. 17.

The plot is arranged to show the most impactful variable at the top. The length of each bar represents the magnitude of the LCOE's response to the change in that parameter. The results clearly indicate that the LCOE is most sensitive to the initial CAPEX. A 20% fluctuation in the upfront investment cost leads to a substantial change of over \$10/MWh in the final LCOE. The discount rate, which reflects the cost of capital, appears to be the second most influential factor.

Interestingly, annual OPEX has a comparatively minor effect on the LCOE. Furthermore, the energy price shows no impact whatsoever. This is an expected and important finding, as the LCOE is a measure of the lifetime cost of energy production and is therefore independent of the revenue generated from electricity sales. The primary takeaway from this analysis is that the financial success of an AWE project in this context is most critically dependent on controlling the initial capital investment and securing favorable financing terms.

E. AWE VERSUS HAWT

Fig. 18 presents a classic trade-off between the innovation of AWE and the maturity of HAWTs. AWE has a clear advantage in environmental friendliness and tapping into better wind resources. Yet, HAWTs remain ahead on technical readiness, economics, and policy support. Ultimately, AWE is a technology with high potential, but it must first navigate the developmental and regulatory hurdles that HAWTs have long since cleared. Presently, AWE technology

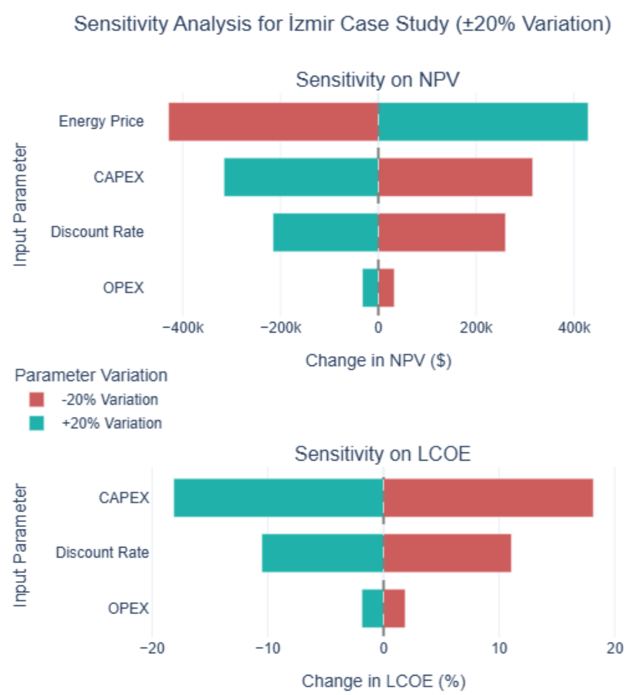

FIGURE 17. Tornado plot illustrating the sensitivity of NPV and LCOE to ±20% variations in key economic parameters for the İzmir site.

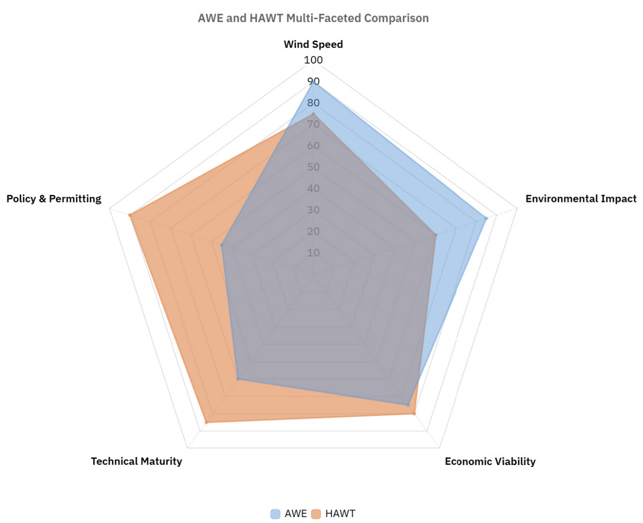

FIGURE 18. General comparison of AWE and HAWT systems.

is assessed at Technology Readiness Levels (TRL) 6-7, indicating that pilot-scale systems have been demonstrated under relevant conditions, but full commercial deployment; including long-term reliability, autonomous operation, and regulatory approval, remains pending [19].

IV. CONCLUSION

This study conducted an integrated assessment of the potential for Airborne Wind Energy (AWE) systems in ten promising regions across Türkiye, combining statistical wind resource modeling with life cycle and techno-economic analyses. Our findings suggest that AWE represents a viable and potentially advantageous technology for inclusion in Türkiye's renewable energy strategy, particularly in coastal regions with high-quality, high-altitude wind resources. The analysis of wind data revealed that the Gamma distribution provides a more accurate characterization of wind speed profiles than the commonly used Weibull model in most of the studied locations.

The LCA indicated a clear environmental advantage for AWE systems, particularly in high-potential areas like Çanakkale, where the GWP was calculated as low as 7.4 gCO_2-eq/kWh, with 7.2 gCO_2-eq/kWh in İzmir. Economically, the results now show a much wider and more realistic range of outcomes. The Levelized Cost of Electricity (LCOE) is as low as \$0.042/kWh in Çanakkale but rises to over \$0.16/kWh in Aydın, a site with a less favorable wind profile. This highlights the critical importance of site selection. The most promising locations for investment are Çanakkale and Kırklareli, which showed the highest Net Present Values (NPV) and Internal Rates of Return (IRR) exceeding 16%, with payback periods under 7 years. These findings confirm that AWE systems hold significant technical promise and appear economically viable in Türkiye's best-performing regions.

To properly contextualize these economic findings, it is useful to compare them against the current benchmarks for conventional Horizontal Axis Wind Turbines (HAWTs) in Türkiye. Our projected LCOE for a high-potential site like Çanakkale, at \$0.042/kWh, appears not just competitive, but on par with the very latest conventional turbine technologies. A recent 2023 study, for example, calculated the LCOE for modern turbines from leading manufacturers to be between \$0.043/kWh and \$0.061/kWh [47]. This suggests that a mature AWE system could potentially match or even slightly outperform the most efficient HAWTs available today. This stands in stark contrast to the landscape just over a decade ago, when the LCOE for wind power in Türkiye was estimated to be as high as \$0.15/kWh [48], illustrating just how far the technology has come and the potential window of opportunity for AWE.

However, this study's conclusions are subject to several limitations that must be acknowledged. The wind resource assessment relied on a power law extrapolation of 100 m data, which introduces uncertainty that could only be fully resolved with direct high-altitude measurements (e.g., via LIDAR). The analysis was based on a single reference AWE design, and the economic projections are for a pre-commercial technology (TRL 6-7), meaning that cost estimates carry a higher degree of uncertainty than for mature technologies. Furthermore, our discussion of non-technical barriers, while important, was qualitative and warrants a more in-depth investigation.

Future research should prioritize several key areas to build upon this work. First, validation of high-altitude wind resource models using empirical data from remote sensing is crucial for reducing uncertainty in energy yield predictions.

Second, comparative LCA and TEA studies should be conducted on different AWE architectures (e.g., fly-generation vs. ground-generation) to identify optimal designs for the Turkish context. Finally, detailed socio-political studies are needed to investigate public acceptance and develop a clear regulatory framework to facilitate the responsible and efficient deployment of AWE technology in Türkiye.

Finally, it is worth remembering that technical feasibility and economic viability alone do not guarantee successful deployment. Social and policy barriers are often just as, if not more, challenging [49], [50]. For a novel technology like AWE in Türkiye, a few key issues would likely come to the forefront. First, there is the question of regulation; clear rules for managing airspace and for siting ground stations would need to be established, as current frameworks were designed with conventional turbines in mind. Beyond that, there is the matter of public perception [51]. While AWE systems have a different visual profile than traditional turbines, issues of safety, noise, and visual impact would still need to be addressed through transparent planning and clear communication with local communities to build trust and gain acceptance.

APPENDIX

CODE AVAILABILITY

The MATLAB® code developed for the probabilistic wind modeling presented in this study is not publicly archived at this time, as it forms part of an ongoing doctoral thesis. However, the code is available from the corresponding author upon reasonable request. Also, the rationale used in the creation of the code can be found in prior studies [52].

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