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Airborne Wind Energy in Turkey with a Focus on Wind Resource Life Cycle Assessment and Techno-Economic Analysis

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Abstract—**Airborne wind energy (AWE) technology has emerged as a promising alternative to conventional wind turbines, harnessing stronger and more consistent winds at higher altitudes. This paper explores the potential of AWE systems in Turkey through a case study of the Hatay region. The study begins with the selection of the optimal two-parameter Weibull distribution model and compares various parameter estimation methods to accurately estimate wind speeds using wind speed data. This analysis is followed by a life cycle assessment (LCA) to quantify the global warming potential (GWP) and cumulative energy demand (CED) associated with the deployment of an AWE plant in Turkey. Additionally, a techno-economic assessment evaluates the economic viability of AWE systems over their operational lifetime through detailed cost modelling. Experimental verifications and comparisons with existing renewable energy technologies are also presented to validate the findings. The results demonstrate that AWE systems offer significant environmental and economic benefits, providing critical insights for policymakers, investors, and stakeholders. This study not only contributes to the growing body of AWE research, but also offers a replicable methodological framework for assessing AWE potential in other regions with similar wind energy prospects.**

Index Terms—**Airborne wind energy; Life cycle assessment; Techno-economic analysis; Wind energy assessment.**

I. INTRODUCTION

Airborne wind energy (AWE) represents a transformative approach to harnessing wind power, leveraging the potential of higher altitude winds which are more consistent and potent than surface winds. This study focusses on Turkey, a region with great potential for wind energy, to assess the feasibility and sustainability of AWE systems. The primary motivation behind this research is to address the growing demand for sustainable energy solutions by exploring the feasibility and environmental impact of AWE systems. Traditional wind energy systems are limited by ground-level wind inconsistencies and land use conflicts, which AWE systems can potentially overcome. By integrating wind resource assessment, life cycle assessment (LCA), and techno-economic assessment (TEA), this research provides a novel and comprehensive evaluation of AWE systems, addressing their energy generation capabilities, environmental impacts, and economic potential. The motivation behind this study is to contribute to the global effort for sustainable energy transition, specifically tailored to the regional characteristics and needs of Turkey.

Despite the promising advances in renewable energy technologies, there remains a critical need to address the intermittency and geographical limitations of traditional wind energy systems. The scientific problem at the heart of this study is the assessment of airborne wind energy (AWE) systems as a viable alternative to conventional wind turbines, particularly in regions such as Turkey with varying wind resources. This involves determining whether AWE systems can reliably harness high-altitude winds to provide consistent energy output while minimising environmental impacts. The study also seeks to identify the optimal locations for AWE deployment in Tukey and to compare the environmental footprint of AWE systems with that of traditional wind energy technologies through LCA.

AWE has gained traction in Europe and North America for its ability to harness high-altitude winds, use fewer materials, simplify installations, and provide versatility for both onshore and offshore applications, with investments of $200 million from corporations such as Google, EON, Shell, Schlumberger, Tata, and Softbank [1]. AWE has advanced significantly in R&D, though challenges such as the durability of tether systems under high stress remain. AWE systems also have some limitations, primarily due to tether drag [2]. A study highlights that the drag of the tether can increase by up to 300 % due to vortex-induced vibration and by 210 % due to galloping, severely affecting the efficiency of the system [2]. To address this problem, dual-airfoil systems have been proposed, which can significantly reduce the overall drag of the system and improve efficiency, especially on small and medium scales [3]. Despite these challenges, AWE offers advantages over traditional windmills, including the ability to access higher wind speeds and overcome some technical and non-technical limitations of conventional systems [4]. The ongoing research and technological advancements in the design and operation of

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AWEs are crucial to overcome these limitations and to realise the full potential of this innovative renewable energy technology.

AWE presents transformative potential for wind energy [5], promising up to tenfold cost reductions compared to traditional wind turbines due to its use of ground-based generators [6]. Studies demonstrate the capacity of AWE for continuous and sustainable power generation, which is crucial for regions with energy deficits [7]. Resource assessments indicate that AWE can significantly boost energy yield by accessing high-altitude winds and optimising dynamic resource harvesting [8].

Recent research has explored various aspects of AWE, including floating offshore farms, drivetrain innovations for power smoothing, and system designs considering fluctuating electricity prices and market integration [9]–[12]. Research in areas such as Tamil Nadu and various energy storage scenarios emphasises the need for integrated AWE solutions [13], [14]. Building on these advances, this study evaluates the viability of AWE in Hatay, Turkey, using wind data from the Global Wind Atlas, indicating average wind speeds of over 7 m/s at 100 meters [15]. The study includes wind resource evaluation, LCA, and TEA, informed by previous studies, offering information for policy and investment decisions [16].

Hatay emerges as an optimal candidate for AWE deployment due to its high wind energy potential, with mean wind speeds exceeding 7 m/s at 100 meters (Fig. 1).

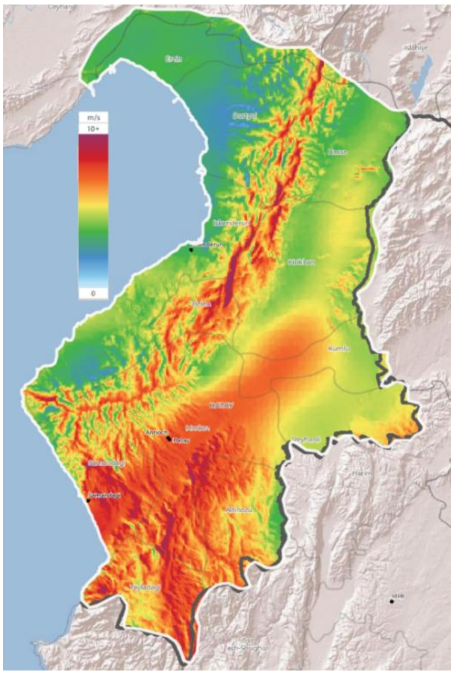


Fig. 1. Hatay province average wind speed at 100 m height.

The complex topography of the region, which includes coastal plains, rolling hills, and mountains, creates favourable wind patterns for AWE systems. Moreover, logistical advantages such as proximity to highways, seaports, and airports support the deployment of AWE, while available land and lower population densities minimise land-use conflicts. Hatay's economy, primarily based on agriculture and tourism, aligns with sustainable development goals, making AWE an attractive option to diversify energy sources and reduce emissions.

II. WIND DATA ASSESSMENT

The wind resource assessment for the deployment of AWE in Hatay used wind data at 100 meters altitude from the MERRA-2 reanalysis product, focussing on hourly data for 2023. This assessment aimed to characterise the wind regime and evaluate 14 different Weibull parameter estimation methods to determine the most suitable approach.

A. *Methodology*

The Weibull distribution scale and shape parameters have been commonly derived by modelling wind speed frequencies, using various estimation methods outlined in Table I. Comparative analysis was conducted through a custom MATLAB code was conducted against real wind data measurements (Fig. 2). Among the methods, the novel energy pattern factor method (NEPFM) and the maximum likelihood method (MLM) showed the closest agreement with actual wind data (Fig. 3 and Table II).

TABLE I. PARAMETER ESTIMATION METHODS USED IN THIS STUDY.

Parameter Estimation Method	Abbreviation	Source
Graphical Method	GM	[17]
Maximum Likelihood Method	MLM	[18]
Modified Maximum Likelihood Method	MMLM	[19]
Energy Pattern Factor Method	EPFM	[20]
Wind Energy Intensification Method	WEIM	[21]
Justus Moment Method	JMM	[22]
Novel Energy Pattern Factor Method	NEPFM	[22]
Power Density Method	PD	[23]
Lysen Method	LM	[24]
Method of Moments	MOM	[25]
Mabchour's Method	MMAB	[26]
Alternative Maximum Likelihood Method	AML	[27]
Rayleigh Distribution	Ray	[28]
Least Squares Method	LSM	[29]

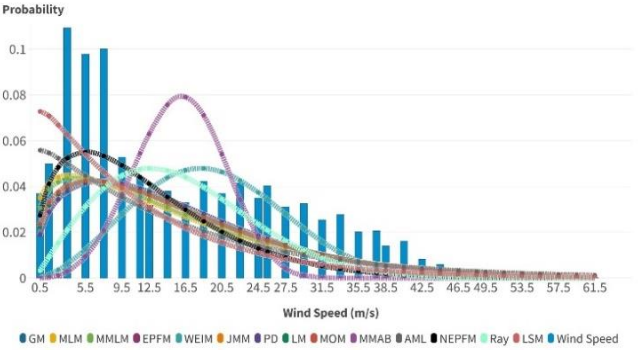


Fig. 2. Comparison of all 14 parameter estimation methods: Wind data vs. parameter estimation methods.

TABLE II. NUMBER OF DATA POINTS THAT ARE CLOSEST TO THE ACTUAL DATA.

Parameter Estimation Method	Number of Data Points
NEPFM	12
WEIM	8
AML	5
MLM	2
Ray	2
GM	1
MMLM	1
EPFM	1
MOM	1
MMAB	1
LSM	1
JMM	0

Parameter Estimation Method	Number of Data Points
PD	0
LM	0

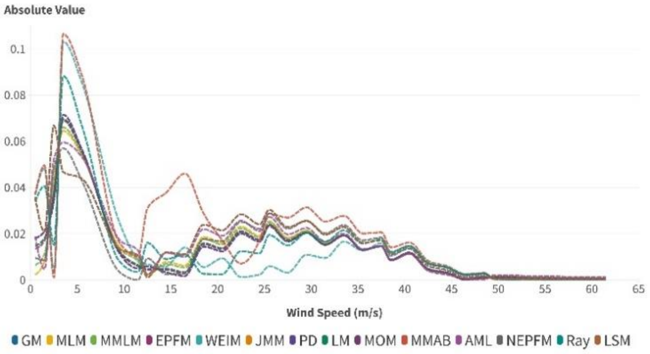


Fig. 3. Performance comparison of parameter estimation methods: Absolute value based on wind data for each method.

B. *Performance Evaluation*

The performance analysis (Fig. 3 and Table II) indicated that NEPFM and WEIM provided the highest accuracy. Metrics such as WEE, RMSE, R-squared (R²), and Chi-squared (χ²) were used for error analysis.

Table III compares the error values, where the lower values are better for all metrics except R², which is evaluated based on the highest value. The characteristics and evaluation criteria of each metric are detailed in Table IV.

TABLE III. COMPARISON OF ERROR VALUES FOR EACH PARAMETER ESTIMATION METHOD.

	WEE	RMSE	R^2	χ^2
GM	0,2683	0,2825	0,9304	2,60E-05
MLM	0,3037	0,1790	0,9888	4,20E-06
MMLM	0,2286	0,1850	0,9872	4,78E-06
EPFM	0,0031	0,2147	0,9767	8,69E-06
WEIM	0,0698	0,3783	0,7760	8,37E-05
JUS	0,0663	0,2042	0,9810	7,11E-06
PD	4,6E-09	0,2142	0,9770	8,61E-06
LYS	0,0686	0,2043	0,9810	7,12E-06
MOM	0,0922	0,2007	0,9823	6,63E-06
MMAB	0,5742	0,3877	0,7529	9,23E-05
AML	0,8205	0,1844	0,9874	4,72E-06
NEPFM	0,5465	0,2783	0,9344	2,45E-05
RAY	0,3647	0,2985	0,9132	3,24E-05
LSM	0,2683	0,2825	0,9304	2,60E-05

TABLE IV. EVALUATION OF ERROR VALUES FOR EACH METHOD.

Rank	WEE	RMSE	R^2	χ^2	Result
1	PD	MLM	MLM	MLM	MLM
2	EPFM	AML	AML	AML	AML
3	JUS	MMLM	MMLM	MMLM	MMLM
4	LYS	MOM	MOM	MOM	MOM
5	WEIM	JUS	JUS	JUS	JUS
6	MOM	LYS	LYS	LYS	LYS
7	MMLM	PD	PD	PD	PD
8	LSM	EPFM	EPFM	EPFM	EPFM
9	GM	NEPFM	NEPFM	NEPFM	NEPFM
10	MLM	LSM	LSM	LSM	LSM
11	RAY	GM	GM	GM	GM
12	NEPFM	RAY	RAY	RAY	RAY
13	MMAB	WEIM	WEIM	WEIM	WEIM
14	AML	MMAB	MMAB	MMAB	MMAB

C. *Conclusion of the Wind Data Assessment*

The MLM exhibited the lowest overall error for Hatay, with the AML and MMLM methods closely following. For wind power calculations, the PD, EPFM, and JUS methods best estimated the power density, closely aligning with actual values (Fig. 4).

Fig. 4. Comparison of the density of the wind power.

In conclusion, NEPFM was the most effective for wind speed estimates in Hatay, while the PD method was most accurate for wind power calculations.

III. LIFE CYCLE ASSESSMENT

As Turkey diversifies its renewable energy portfolio, it is essential to assess the environmental impacts of emerging technologies such as AWE. This study conducts a life cycle assessment (LCA) of a hypothetical 50 MW AWE plant in the wind-rich Hatay region, comparing it to a theoretical 50 MW horizontal axis wind turbine (HAWT) farm to evaluate the full environmental impact.

A. *Software Evaluation*

For LCA, various software options were considered. OpenLCA was chosen due to its compatibility and widespread use in renewable energy assessments. Initial evaluations included other programmes such as GaBi, SimaPro, Umberto, and Ecochain.

B. *Data Set Acquisition*

A systematic data set assembly process involved:

1. *Literature Research*: Extensive searches in academic data bases and repositories to identify AWE LCA literature;
2. *Selection Criteria*: Screening literature for quality, AWE focus, and comprehensiveness;
3. *Data Extraction*: Gathering data on materials, their environmental impacts, production, and use from selected sources;
4. *Data Verification*: Evaluating data for accuracy and consistency;
5. *Data Compilation*: Compiling verified data into an Excel spreadsheet, recording material masses, global warming potentials, cumulative energy demands, and life-cycle evaluations.

C. *LCA Methodology*

LCA is a systematic procedure to evaluate the environmental impact of a product or service system throughout its lifecycle [30]. The LCA followed a systematic procedure (Fig. 5) consisting of:

1. *Defining Project Goals and Scope*: Identifying the purpose, boundaries of the system, and functional unit for evaluating AWE in Turkey [31];
2. *Inventory Analysis*: Conducting literature research, data extraction, verification, and compilation to quantify the inputs and outputs of the AWE system [32];

3. *Impact Assessment*: Recording and calculating environmental impact indicators such as energy consumption, greenhouse gas emissions, and cumulative energy demand [30];
4. *Analysis of Results*: Summarising and discussing the results of the inventory analysis and impact assessment against the defined goals and scope [30].

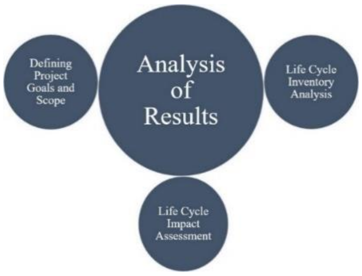


Fig. 5. Life cycle assessment stages [16].

D. LCA Results and Interpretation

The LCA revealed that AWE systems are more material-efficient, using significantly less material per MWh generated compared to HAWTs. This efficiency comes from optimised material use and access to high-altitude wind resources with greater energy density. The AWE systems exhibited a lower global warming potential (GWP) and cumulative energy demand (CED), reducing environmental burdens (Figs. 6–8).

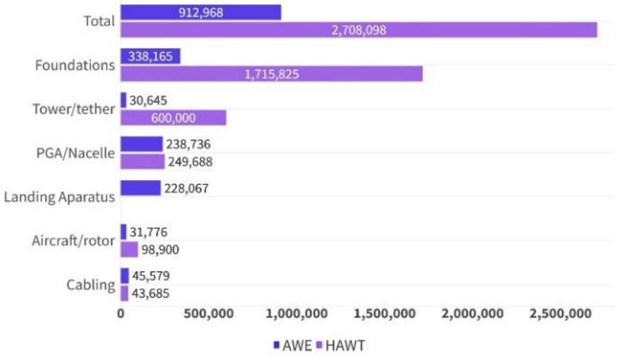


Fig. 6. The masses of AWE and HAWT systems (for 50 MW installed AWE and HAWT farms, in kg).

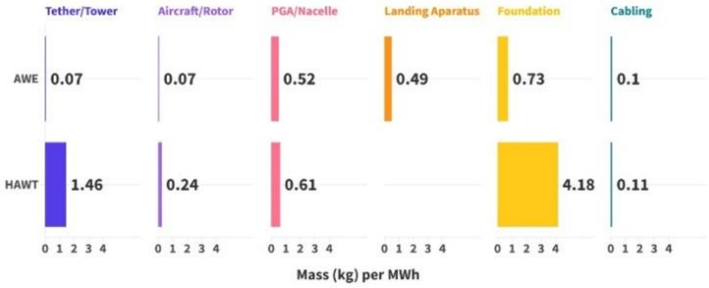


Fig. 7. Masses of AWE and HAWT based on the MWh produced.

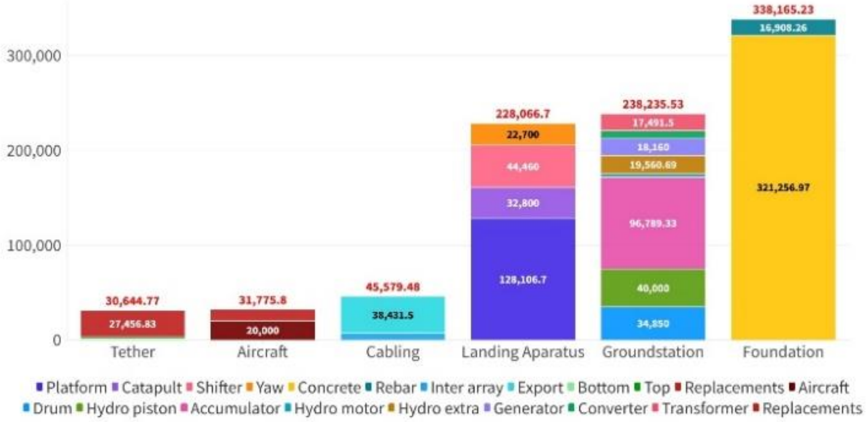


Fig. 8. Masses of the AWE system per each submaterial [kg].

Figures 9 and 10 illustrate that AWE systems demonstrate roughly half the GWP and a lower CED than HAWTs for generating 1 MWh of electricity.

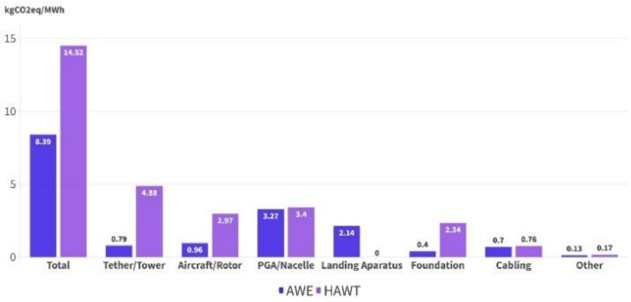


Fig. 9. GWP for both AWE and HAWT for the MWh produced.

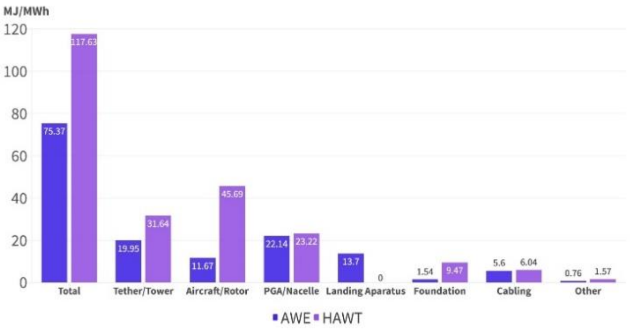
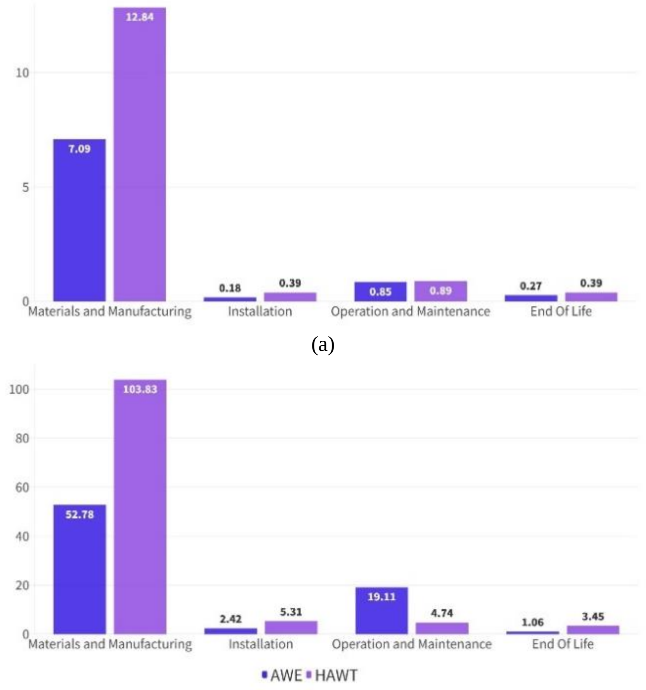


Fig. 10. CED for both AWE and HAWT for the MWh produced.

However, higher CED values were observed for AWE operations and maintenance due to frequent maintenance visits, component replacements, and lubrication needs, as shown in Fig. 11.



(a)

(b)

Fig. 11. (a) GWP (kgCO2eq/MWh) and (b) CED (MJ/MWh) for AWE and HAWT for the life cycle stages.

IV. TECHNO-ECONOMIC ASSESSMENT

This study evaluates the economic feasibility and financial implications of AWE systems in Turkey, specifically in the Hatay region.

A. TEA Methodology

The TEA employs a structured approach, adhering to established practices in renewable energy economics. It incorporates site-specific factors such as wind characteristics, topography, and logistics for the AWE plant (Fig. 12) to ensure accurate economic projections.

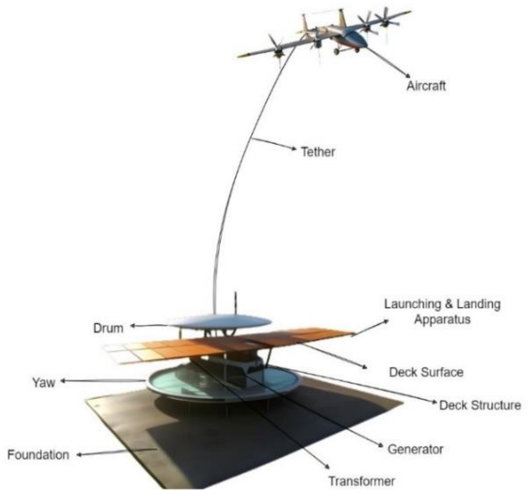


Fig. 12. A breakdown of an AWE plant.

The CAPEX analysis evaluates initial investment costs, including airborne components, ground stations, ancillary equipment, land acquisition, and installation expenses (Fig. 13).

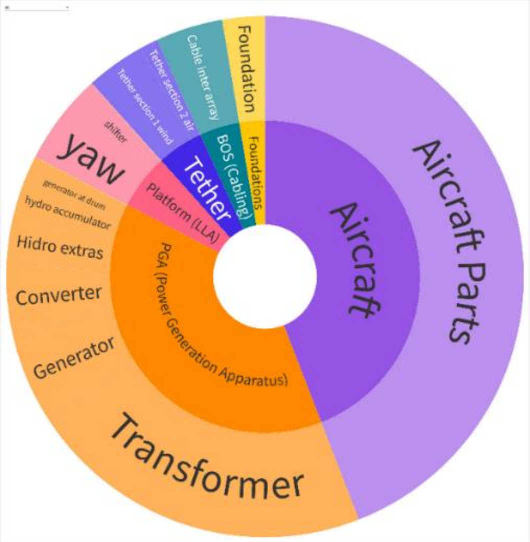


Fig. 13. All parts of the AWE plant and their effects on CAPEX.

The OPEX covers recurring costs throughout the life of the AWE plant, including maintenance, repairs, replacements, monitoring, control systems, and potential downtime or performance losses (Fig. 14). It also includes labour costs, material requirements, and other operational overheads.

Fig. 14. Operating expenses of the AWE plant.

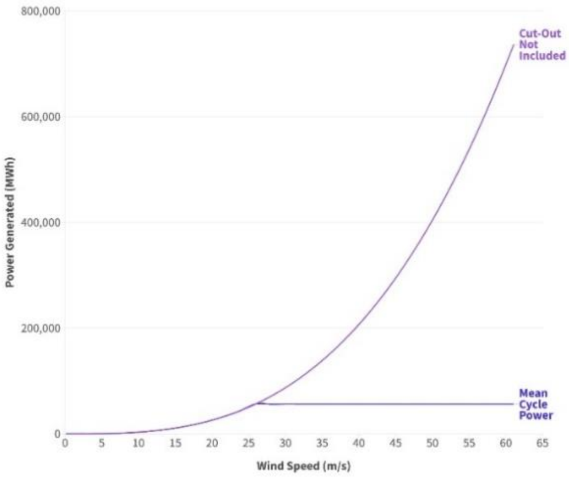


Fig. 15. Power curve for the AWE plant.

The levelised cost of energy (LCOE) calculation assumes a 20-year project life with an 8 % discount rate. LCOE is derived from the sum of discounted costs divided by the sum of discounted energy production:

Discounted CAPEX = \$750.000;

Discounted annual OPEX = \$90.000/(1/1 + 0.08)^t, where t is the year (1 to 20).

Figure 15 shows details of the calculated power curve of the AWE plant in Hatay. The cut-out power is taken 25 m/s from the literature [33].

B. Economic Modelling and Analysis

The techno-economic assessment incorporates a financial model that integrates CAPEX, OPEX, energy production estimates, and other relevant economic parameters.

This model facilitates the calculation of key economic indicators, including the levelised cost of energy (LCOE), net present value (NPV), internal rate of return (IRR), and payback period. The necessary calculations and equations used can be seen in Table V.

Table VI provides a comparison of TEA on AWE with literature studies on HAWT systems.

TABLE V. TEA CALCULATIONS.

Financial model assumptions:

- Project lifetime: 20 years;
- Discount rate: 8 %;
- CAPEX: \$750,000;
- Annual OPEX: \$90,000;
- Annual energy production (AEP): 76 GWh;
- Feed-in tariff: \$0.073 per kWh (\$73 per MWh).

The expected annual revenue for the proposed 50 MW AWE plant in Hatay, based on the feed-in tariff and estimated AEP, is calculated as in [34]

$$Annual\ Revenue = 76{,}000\ MWh \times \frac{\$73}{MWh} = \\ = \$5{,}548\ Million. \quad (1)$$

Step 1: Calculating the sum of discounted costs

Sum of discounted annual OPEX (present value of an annuity formula) [35]:

$$= \$90{,}000 \times \sum_{t=1}^{20} \frac{1}{(1+0{,}08)^t} = \\ = \$90{,}000 \times 9{,}818 = \$883{,}620. \quad (2)$$

Sum of discounted costs [35]:

= Discounted CAPEX + Sum of discounted annual OPEX

$$= \$750{,}000 + (\$90{,}000 \times 9{,}818) = \\ = \$1{,}634\ Million. \quad (3)$$

Step 2: Calculating the sum of discounted energy production

Discounted annual energy production

Sum of discounted energy production (present value of the annuity formula) [35]:

$$= 76{,}000\ MWh \times \sum_{t=1}^{20} \frac{1}{(1+0{,}08)^t} = 76{,}000\ MWh \times \\ \times 9{,}818 = 746{,}168\ MWh. \quad (4)$$

***Calculating the LCOE* [35]**

$$LCOE = \frac{\sum Discounted\ costs}{\sum Discounted\ energy\ production} \quad (5)$$

$$= \frac{\$1{,}634\ Million}{746{,}168\ MWh} = \frac{\$0{,}0022}{kWh}\ or\ \frac{\$2{,}2}{MWh}. \quad (6)$$

***Net present value (NPV) calculation* [9]**

$$NPV = Initial\ Investement + \\ + Sum\ of\ Discounted\ Cash\ Flows, \quad (7)$$

$$Annual\ Cash\ Flow = Annual\ Revenue - \\ - Annual\ OPEX \quad (8)$$

$$= (AEP \times PPA\ rate) - Annual\ OPEX. \quad (9)$$

In (9), AEP is short for annual energy production, and PPA is a power purchase agreement

$$= \left(76{,}000\ MWh \times \frac{\$73}{MWh}\right) - \$90{,}000 = \\ = \$5{,}458{,}000. \quad (10)$$

Discounted cash flow

$$= \frac{Annual\ Cash\ Flow}{(1+Discount\ Rate)^t} = \frac{\$5{,}458{,}000}{(1+0{,}08)^t}, \quad (11)$$

where t is the year 1 to 20.

Sum of Discounted Cash Flows

$$= \$5{,}458{,}000 \times \sum_{t=1}^{20} \frac{1}{(1+0{,}08)^t} = \\ = \$5{,}458{,}000 \times 9{,}818 = \$53{,}586{,}644, \quad (12)$$

where t is the year 1 to 20.

$$NPV = -\$750{,}000 + \$53{,}586{,}644 = \$52{,}836{,}644. \quad (13)$$

The internal rate of return (IRR) is the discount rate at which the NPV becomes zero. Since we do not have a closed-form solution, we can use trial and error or numerical methods to find the IRR. Using Excel's IRR function with the cash flow series (-\$750,000, \$5,458,000, \$5,458,000, ..., \$5,458,000), the IRR is approximately 148 %.

Payback period calculation

The payback period is the number of years it takes to recover the initial CAPEX from the annual cash flows.

Annual cash flow = \$5,458,000.

$$Payback\ Period = \frac{CAPEX}{Annual\ cash\ flow} = \\ = \frac{\$750{,}000}{\$5{,}458{,}000} = 0{,}14\ years\ or\ approximately\ 50\ days. \quad (14)$$

TABLE VI. COMPARISON OF AWE TO HAWT FOR TEA.

Criteria	AWE	HAWT [36], [37]
Power Coefficient	With %53–55 reeling factor	%35–40
Annual Generation	76 GWh	3.8 GWh (500 kW turbine) in certain cases, depending on regional wind conditions
Levelised Cost of Energy - LCOE	0.2 cent/kWh	2007 → 15 cent/kWh 2023 → LCOE for Goldwind, Vestas, and GE are 0.043 USD/kWh, 0.061 USD/kWh, and 0.056 USD/kWh, respectively.
Installation Cost	Expected lower	Higher; for a typical 500 kW turbine 750,000 USD (depending on the region)
Power Density	Higher (more energy use)	Typically lower
Flexibility	High; ability to harvest energy at various heights	Fixed height; limited to wind turbine tower height
Payback Time	Potentially shorter	Variable by region and turbine capacity; 4–10 years in examples
Net Present Value - NPV	Expected to be more advantageous; lower costs envisaged for AWE	Typical low; due to high installation costs
Economic Usability	Developing; no commercial systems yet	More established and commercially available

V. DISCUSSION

Contribution to the discourse on renewable energy. This study makes the following key contributions to the field of airborne wind energy (AWE).

1. Wind resource assessment: The research identifies optimal methods to calculate the two-parameter Weibull distribution for AWE deployment in Turkey, analysing 12 months of wind speed data.
2. Life cycle assessment (LCA): A detailed LCA compares the environmental impacts of AWE systems with traditional wind energy, showing a significantly lower ecological footprint and reduced greenhouse gas emissions.
3. Technological feasibility: The study evaluates the technical viability of AWE systems in Turkey, considering wind consistency, altitude, and technological readiness.
4. Socio-economic implications: The research highlights broader socio-economic benefits, including job creation, energy security, and contributions to national renewable energy targets.

Key results indicate that AWE systems consistently harness higher altitude winds, providing a reliable and sustainable energy source with reduced environmental impact compared to conventional wind turbines. TEA shows the economic potential of AWE over HAWT systems based on reduced material usage and lifetime costs.

Experimental verification. Recent experimental studies on AWE demonstrate their operational viability and performance metrics. The dynamic analysis of the rotary AWE machines, through simulations and field tests, showed stable angular velocities and consistent tension. Experiments confirmed the ability of the system to handle external torques and accurately predict resonance frequencies, addressing critical real-world scenarios such as resonance-induced collapses [38].

The advancements of Ampyx Power in tethered UAV systems show commercial scalability. Their UAVs, optimised for power generation, feature robust safety and redundancy, ensuring operational reliability and compliance with aviation standards. Extensive testing has validated their performance, safety, and economic feasibility [39], [40].

VI. CONCLUSIONS

This study has evaluated the viability and sustainability of AWE technology in Hatay, Turkey. Key findings reveal that the novel energy pattern factor method is the most suitable for estimating wind speeds in Hatay, and the power density method showed the lowest error in wind power calculations. These methodologies provided accurate annual energy production estimates, which are crucial for subsequent techno-economic analysis. The LCA indicated that AWE systems have several advantages over HAWTs, including reduced material usage, lower global warming potential, and lower cumulative energy demand. However, AWE systems also exhibited higher operational impacts and end-of-life uncertainties, indicating the need for further research and optimisation. The TEA demonstrated the economic feasibility of AWE systems through favourable levelised energy cost, net present value, and internal rate of return metrics. Revenue projections supported by realistic power purchase agreement rates and potential incentives further reinforced the economic attractiveness of AWE systems. The implications for stakeholders are significant. Policy makers can use these results to support decisions about the adoption of AWE technology, contributing to a diversified and sustainable energy mix. Investors are presented with compelling economic indicators for investment in AWE systems that showcase their potential for competitive returns. Industry professionals gain a practical understanding of the integration challenges and benefits of AWE, which guide future development and deployment strategies. In conclusion, this study offers valuable insights into the potential of AWE systems in Hatay, highlighting their environmental and economic benefits, while also addressing the need for ongoing research to optimise their operational performance and lifecycle impacts.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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