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Comparative Life Cycle Assessment of Airborne Wind Energy and Horizontal Axis Wind Turbines in Türkiye

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***Abstract*—As the global demand for clean and sustainable energy sources continues to rise, the quest for innovative and environmentally friendly technologies becomes increasingly imperative. With growing concerns about climate change and the need to transition away from fossil fuels, understanding the environmental impacts of emerging technologies like Airborne Wind Energy (AWE) is crucial for shaping the future of energy production. This paper presents a Life Cycle Assessment (LCA) of a theoretical AWE plant in Türkiye, comparing it to traditional horizontal axis wind turbines. The study aims to determine the feasibility of installing AWE plants in Türkiye and their environmental impact. Results show that AWE plants use less material and generate electricity with lower impacts than traditional turbines, making them a viable option for renewable energy generation in Türkiye.**

Keywords— wind energy, life cycle assessment, airborne wind energy, environmental impact.

I. Introduction

The urgency to combat climate change has ignited interest in renewable energy as an alternative to fossil fuels, demanding a comprehensive understanding of existing energy systems [1]. Renewable sources like solar, wind, hydro, biomass, and geothermal power offer solutions to reduce greenhouse gas emissions and address climate change [2, 3].

The International Energy Agency predicts renewables will surpass coal, constituting over 90% of global electricity expansion within five years [4], reflecting the global commitment to a sustainable, low-carbon energy system [4]. In alignment with this shift, Airborne Wind Energy (AWE) systems, designed to capture wind energy at higher altitudes using flying devices like kites or drones, offer potential advantages over traditional wind turbines [5, 6], including reduced environmental im- pacts due to consistent, stronger winds and decreased infrastructure needs.

However, AWE systems face challenges such as technical feasibility, reliability, safety, regulation, and societal acceptance. Their environmental performance depends on various factors, highlighting the importance of Life Cycle Assessment (LCA) studies [5, 6].

Recent LCA studies reveal that AWE systems exhibit a higher capacity factor and lower energy cost per unit, especially at high altitudes and offshore locations with abundant wind resources [7]. Optimizing design parameters and incorporating power adjustment solutions can further enhance their performance [8, 9].

Floating AWE systems have the potential to exploit offshore wind resources, reducing land use and environmental impacts, albeit with additional challenges [10]. AWE systems generally show lower environmental impacts than traditional wind turbines in areas like greenhouse gas emissions, material use, land use, noise, and aesthetics [11].

The acceptance of AWE systems is influenced by their perceived innovation and environmental benefits but may be hindered by safety, aesthetic, and planning concerns [12]. LCA plays a vital role in evaluating the feasibility, performance, and competitiveness of AWE systems, supporting their development toward cleaner and sustainable energy solutions [5, 6]. AWE, a novel technology, aims to harness powerful and consistent high-altitude winds [13]. Utilizing autonomous flying devices connected to ground-based generators or batteries, these systems can generate electricity onboard or transmit it through a tether [14]. Various AWE typologies, including dual airfoil systems, kite systems, blimps, and airship-lifted wind turbines, are being developed worldwide [15, 16, 17, 18, 19]. Prototypes showcased at the International Airborne Wind Energy Conference in 2015 demonstrated the technology's progress [17].

AWE systems can generate power either onboard the aircraft or on the ground through tether reeling and unreeling. Ground- based generation systems follow a two-phase cycle [18]. A unique concept involves using an airship to lift a wind turbine, producing power on the ground and transmitting it via the tether [19].

Optimal locations for AWE farms are characterized by consistent, high-altitude winds, especially below 3,000 meters [20]. Analysis of global wind data identifies potential deployment areas with wind speeds exceeding 10 m/s below 3,000 m [20], offering the prospect of generating terawatts of power. Our focus is on Airborne Wind Energy (AWE) systems, novel technology harnessing wind energy at higher altitudes than traditional wind turbines [21]. AWE systems, using flying devices like kites or drones, convert mechanical energy into electricity via a tether connected to a ground-based generator. AWE systems have the potential to reduce environmental and material impacts due to lower infrastructure and access to consistent, strong winds [22].

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The environmental performance of AWE systems depends on design, materials, operation, and maintenance, necessitating Life Cycle Assessment (LCA) studies for comparisons with traditional wind turbines and other renewables. LCA evaluates environmental impacts from raw material extraction to disposal or recycling [23], aiding technology assessment and policy development.

This paper investigates an LCA of a theoretical AWE plant in Türkiye, comparing its environmental impact to traditional horizontal axis wind turbines. We aim to contribute to renewable energy research, exploring AWE's potential to reduce greenhouse gas emissions in Türkiye while assessing its environmental footprint and life cycle.

The paper is structured as follows: Section II presents the Software Evaluation, Data Set Acquisition, and LCA Methodology. Section III presents the results of the comparative analysis, accompanied by an in-depth performance evaluation. Finally, Section IV offers concluding remarks.

II. Material and Methods

This paper principally involves assessing available software for conducting a LCA using their respective databases. Given the financial constraints associated with some of these software, the strategy adopted involves utilizing the dataset provided by Ampyx Power, which has been employed in various studies [6].

A. Software Evaluation

Initially, we conducted a study to assess software options for our Life Cycle Assessment (LCA). Existing software programs were examined for their compatibility and capabilities in performing the analysis. How- ever, most encountered programs were either costly or lacked the needed features for AWE-specific LCA due to limited databases.

Our study involved two main steps: software selection and data acquisition. Accessible data for AWE, being an emerging technology, was limited but partially sourced from previous studies.

We evaluated five key LCA software options:

- GaBi;
- openLCA;
- SimaPro;
- Umberto;
- Ecochain.

We considered their datasets and, where possible, used trial versions or open-source software like openLCA. Prior literature suggests Umberto NXT, SimaPro, and GaBi are commonly used for AWE systems.

B. Data Set Acquisition

To conduct an LCA of AWE, we assembled a dataset systematically by extracting data from academic articles, thesis studies, and relevant data repositories. The dataset creation involved the following steps:

1) Literature Research: Extensive searches were performed in academic databases, journals, conference papers, and data repositories to identify AWE LCA-focused literature.

2) Selection Criteria: Identified literature was scrutinized based on predefined criteria, considering research quality, AWE LCA focus, and data comprehensiveness.

3) Data Extraction: Selected articles and theses were examined to extract data on materials used in AWE systems and their environmental impacts, including material types, quantities, production, transportation, and usage.

4) Data Verification: The extracted data were critically evaluated for accuracy, consistency, and reliability.

5) Data Compilation: We created an Excel spreadsheet to compile the data, recording material masses, global warming potentials, cumulative energy demands, and life-cycle evaluations.

C. LCA Methodology

LCA is a systematic procedure for evaluating the environmental impact of a product or service system throughout its life cycle [24]. In this paper, we adopted the LCA approach to assess the environmental impacts of AWE systems in Türkiye. As also shown in Fig. 1, the LCA methodology comprises four interconnected stages:

1) Defining Project Goals and Scope: In this initial planning stage, we identified the purpose, system boundaries, and functional unit for assessing AWE systems in Türkiye [25, 26].

2) Inventory Analysis: Extensive literature research, data extraction from selected sources, verification, and data compilation were conducted to quantify relevant inputs and outputs of AWE systems in Türkiye [26].

3) Impact Assessment: This stage involved recording and calculating environmental impact indicators such as energy consumption, greenhouse gas emissions, and cumulative energy demand of each material [24].

4) Analysis of Results: In this final stage, the results of the inventory analysis and impact assessment were summarized and discussed in relation to the defined goals and scope [24].

The primary results of this study, including Global Warming Potential (GWP) and Cumulative Energy Demand (CED), and their derivation for both AWE and traditional Horizontal Axis Wind Turbine (HAWT) systems will be discussed in the following sections.

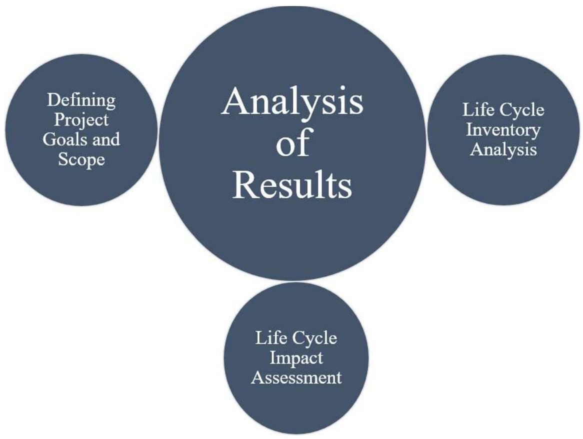

Fig. 1. Life Cycle Assessment Stages.

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III. Results and Discussion

The results have shown that the AWE system requires much less material per generated MWh of energy. This is mainly due to the efficient use of the materials and the AWE plant's setup that allows it to reach the winds with higher potential. The results also highlight the lower global warming potential (GWP) and cumulative energy demand (CED) of AWE systems compared to HAWT.

Fig. 2 illustrates the necessary masses for AWE and HAWT plants. Both exhibit a significant share of mass in their foundations, with the highest value observed in the foundation of the HAWT plant. This reduced mass in the AWE plant results in decreased material usage, leading to lower production costs and a reduced global warming potential.

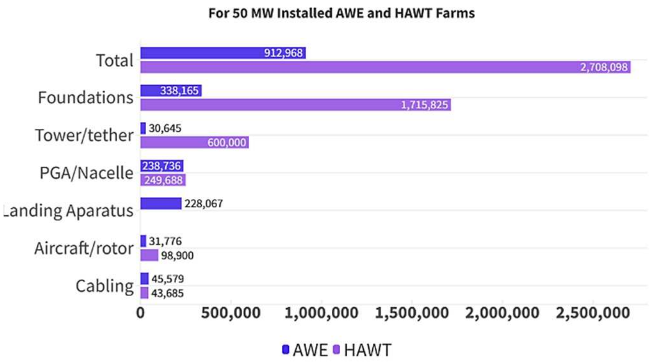

Fig. 2. The Masses of AWE and HAWT Systems.

In Fig. 3, material usage is represented in kilograms. It is evident that, in the HAWT plant, the foundation and tower are the primary contributors to its overall weight. On the AWE system, other than foundation, the main parts that stand out for their masses are the tether, Landing Apparatus, and the ground station (PGA). However, they have lower masses than their counterparts in the HAWT system.

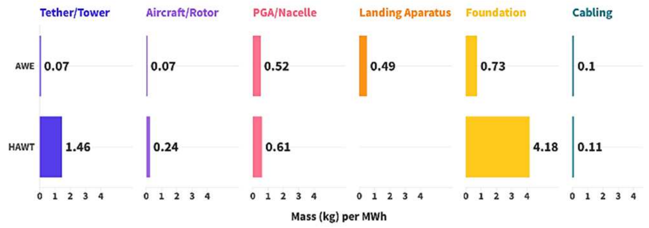

Fig. 3. Masses of AWE and HAWT Based on the Produced MWh.

Fig. 4 displays the weight of each material utilized in the AWE system. All components have been factored into the calculation of GWP and CED, with their weight influencing the GWP.

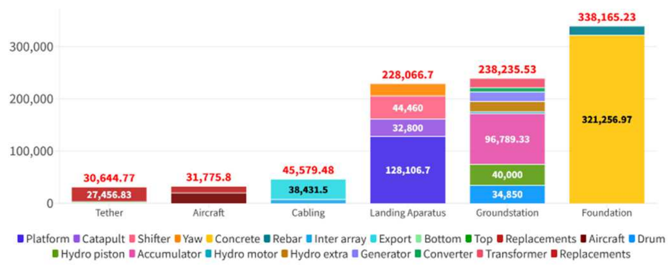

Fig. 4. Masses of the AWE System per Each Sub-Material [kg].

As the quantities increase, the environmental impact generally rises. This trend is evident in Figures 5 and 6, where increased material weight and quantity result in higher global warming potential and cumulative energy demand.

Fig. 5 represents the calculated global warming potential based on each material used in both AWE and HAWT systems. Fig. 5 shows that, since the mass of the AWE system is lower, the amount of materials and the effect they have on global warming is about half that of HAWT system.

Fig. 5. Global warming Potential (GWP) for Both AWE and HAWT for MWh Produced.

According to results, in Fig. 6 the AWE system requires less energy input to generate 1 MWh of electricity (73.37 for AWE, and 117.63 for HAWT).

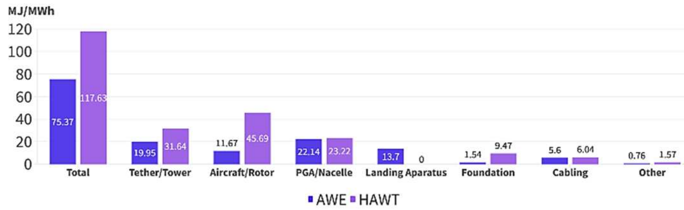

Fig. 6. Cumulative Energy Demand (CED) for Both AWE and HAWT for MWh Produced

Lastly, Fig. 7 shows the amounts for GWP and CED of both AWE and HAWT systems per their life cycle stages.

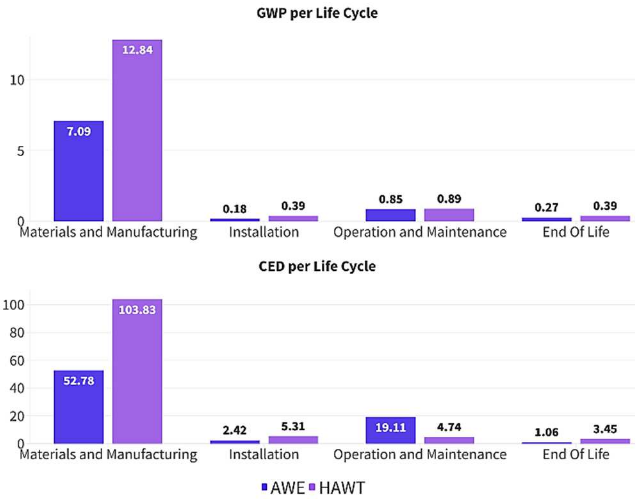

Fig. 7. GWP and CED for AWE and HAWT for Life Cycle Stages.

Expectedly, the AWE system has the lower ratios. However. at the CED value of operation and maintenance, AWE system has a higher value. This is related to a higher number of maintenance visits, replacements of parts for kite/aircraft, and lubrication etc. for the AWE system.

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IV. CONCLUSION

The LCA of AWE and HAWT systems in Türkiye has provided a comprehensive and insightful comparison in this paper. This study holds particular significance given the absence of a physical AWE plant in the country, necessitating a theoretical modeling approach.

Our investigation involved a detailed LCA analysis of a theoretical AWE plant in Türkiye, juxtaposed with a HAWT system. The outcomes of this analysis reveal several compelling advantages associated with AWE, including lower installed mass, reduced global warming potential (GWP), and a lower cumulative energy demand (CED) in comparison to HAWT systems. These benefits can be attributed to decreased material usage, minimized transportation and installation impacts, and a higher capacity factor.

Nevertheless, it's important to acknowledge that AWE is not without its limitations, notably in terms of higher maintenance and operational impacts, coupled with uncertainties surrounding end-of-life scenarios. Furthermore, our study incorporated a comparative element by referencing a prior research effort that relied on European and global LCA databases [25]. Intriguingly, our findings indicate that Turkish AWE and HAWT systems exhibit lower GWP and CED values than their European counterparts. These disparities can be primarily attributed to variations in local environmental factors, electricity generation mix, and material manufacturing processes.

To conclude, AWE undeniably shows promise in mitigating the environmental impacts associated with wind energy generation. Nonetheless, it is evident that further research is imperative to optimize its design, operation, and disposal procedures, paving the way for a more sustainable future in Türkiye's energy landscape.

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