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LCAIRBORNE

Executive summary

Airborne Wind Energy (AWE) is an innovative technology designed to harness wind energy at high altitudes, where winds are stronger and more consistent. By using airborne systems like kites or tethered aircraft, AWE offers a novel approach to renewable energy generation. While small-size systems are being tested in remote locations on land, the large-scale deployment of the technology still requires technical advancements. A promising offshoot of this technology is Offshore Airborne Wind Energy (OAWE), which represents an opportunity to exploit even greater wind resources offshore. However, a careful evaluation of its environmental, economic, and social impacts remains crucial before any further development.

The aim of LCAirborne is to conduct a comprehensive study of OAWE by assessing its environmental impacts, economic viability, and social acceptance, thereby offering an aggregate understanding of its potential benefits and challenges. This study, being the first of this type for this emerging technology, wants to establish a benchmark within the energy sector.

The methodology adopted was multifaceted, beginning with a thorough literature review to assess the state of OAWE. A preliminary design of an OAWE farm, consisting of 500 OAWE systems with an installed power of 2 MW, was developed as the basis for the sustainability assessments. The farm is intended to operate off the coasts of Western Sicily, with each generator connected to a kite via a tether and mounted on a floating platform anchored to the seabed; its main components were sized according to simplified models, either created in-house or available in the literature. Once these design choices were established, the work was divided into three parallel work packages - environmental life cycle assessment, techno-economic analysis, and social acceptance - inheriting the output of the technical design phase.

The literature on Airborne Wind Energy (AWE) depicts a rapidly advancing field. Control of the kite still represents a major challenge, necessary to gain fully autonomous power generation. This is delaying the scale up of the technology with the largest operating systems having a rated power of a few hundred kilowatts. Some cost analyses and life cycle assessments are available in the literature, but they are limited to the onshore deployment of AWE. Concerning social acceptance of AWE, only a couple of studies have been published and they urge to undertake further research in a field that is often discarded or underestimated for highly technical products.

The Life Cycle Assessment followed the ISO 14040 and 14044 for consistency and standardized reviewing, considering 16 impact categories recommended by the EU Environmental Footprint. The functional unit was defined as 1 GWh of electricity delivered to the grid. The Life Cycle Inventory was fed with the output of the farm preliminary design. The Life Cycle Impact Assessment reveals that the most significant environmental impacts are associated with the mooring lines and the maintenance phase. The analysis shows that the climate change impact of the farm is 24.3 tonsCO2eq/GWh, with a cumulative energy demand of 440.6 GJ/GWh, resulting in carbon and energy payback times of 1.5 and 3.3 years, respectively. The latter values highlight the environmental effectiveness of the farm over its 30-year lifespan. The hotspots of the farm life cycle are the life cycle of mooring lines and generators. When compared to a traditional Offshore Horizontal Axis Wind Turbine (OHAWT) farm in the same location with the same lifespan, the OAWE farm performs better in terms of, among others, climate change (OAWE: 24.3 tonsCO2eq/GWh vs OHAWT: 31.3 tonsCO2eq/GWh) and resource use, minerals, and metals (OAWE: 0.26 kgSbeq/GWh vs OHAWT: 1.71 kgSbeq/GWh).

The techno-economic analysis exploited an open-source economic model specific to onshore Airborne Wind Energy; financial metrics were adapted to evaluate the economic viability of deploying an OAWE system and to compare its economic performance with that of an onshore AWE system. Offshore AWE exhibits a Levelized Cost of Energy of 93 EUR/MWh (vs 69 EUR/MWh of onshore AWE) and a payback period of 4 years (vs 3 years of onshore AWE). This performance is explained by the higher Initial Capital Costs (ICC) and Operational and Maintenance Costs (OMC) of OAWE (respectively, 1497 kEUR vs 221 kEUR and 186 kEUR/year vs 26 kEUR/year). The ICC is driven primarily by the need for robust infrastructure, including mooring lines and a platform, while the OMC's major burden is represented by the kite maintenance. Nonetheless, a highly positive Net Present Value guarantees the OAWE economic feasibility.

Finally, social acceptance was investigated through a survey submitted to a community where onshore airborne wind energy is being tested; the survey articulated in a questionnaire for a quantitative analysis and a set of interviews for qualitative insights. The primary concerns among residents include the impact of OAWE on marine life and ocean pollution, as well as visual impact, particularly related to scenic views and proximity to the coastline. Despite these concerns, there was a generally favorable attitude towards OAWE, with respondents recognizing its utility more than its overall goodness. Noise annoyance and safety risks were perceived as minor concerns, and there was a positive correlation between general attitudes towards energy transition and acceptance of OAWE. However, those who frequently visit the coast expressed greater worries about the offshore technology. Insights gathered through the interviews underlined the importance of constant communication and consultation with residents by developers. It emerged that previous energy projects influenced the community's perspectives, with the latter being often altered by disappointment towards political involvement.

This project provides a first all-around picture of Offshore Airborne Wind Energy and lays the groundwork for future research and development. The promising announced future of the technology is supported by results, confirming an OAWE farm as a compelling case for large-scale deployment once the technology is ready.

Key Words

Airborne Wind Energy (AWE), Cost Analysis, Offshore Renewables, Life Cycle Assessment (LCA), Social acceptance

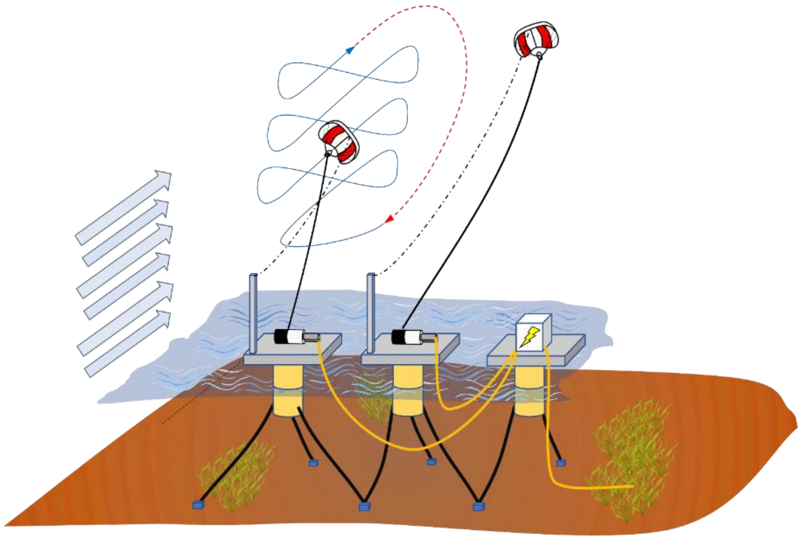

Figure 1: Schematic of an OAWE system

Credit: SkySails

Figure 2: Envisioned OAWE farm from SkySails

Project description written by the Principal Academic Tutor

World energy demand has increased significantly over recent decades, making clean and efficient energy production one of the most crucial challenges. As for wind energy exploitation, the emergence of airborne wind energy is a promising option compared to conventional wind technologies. In particular, the realization of offshore AWE farms also eliminates the problem of land availability of on-ground sites. The goal of this project is to develop a life cycle assessment to evaluate the environmental impact and costs of a hypothetical OAWE farm. Moreover, the analysis would allow one to identify inefficiencies within the actual AWE systems and understand how to improve performance and sustainability, quantifying the impacts by means of standard and customized indicators and adapting AWE to the harsh marine environment. The project is highly multidisciplinary, since the involved aspects range from economic and environmental to technical, as well as social. The main benefits of this work can be resumed in:

- Creating a benchmark in the literature regarding OAWE systems assessment

- Helping developers understanding the main critical points requiring future developments

- Providing policy makers information about AWE potential to accelerate the energy transition

Team description by skill

The LCAirborne project team is composed of five engineering students from Politecnico di Milano and Politecnico di Torino, enrolled in the XIX cycle of Alta Scuola Politecnica (ASP).

Andrea Moino, MSc student in Electrical Engineering, was responsible for sizing the batteries and the transmission lines. He also estimated the net energy production of the farm.

Giovanni Romano, MSc student in Aeronautical Engineering, realized the preliminary design of the aircraft and the tether, and conducted the social acceptance investigation.

Marilù Sagretti, MSc student in Chemical Engineering, focused on the Life Cycle Assessment, performing sensitivity analyses to evaluate different configurations.

Nicola Talia, MSc student in Mechanical Engineering, handled the preliminary design of the platform and mooring lines, while also performing the techno-economic analysis.

Andrea Trebbi, MSc student in Automation and Control Engineering, designed the electric motor and optimized the transmission lines disposal. He also conducted the social acceptance investigation.

Each member of the group had the chance to present their work at the Airborne Wind Energy Conference in Madrid (24-26 April 2024).

Goal

The primary objective of the project is to conduct a sustainability assessment of OAWE through a comprehensive and multidisciplinary study. To achieve this, three key areas of sustainability need to be addressed: environmental, social, and economic. This assessment aims to evaluate the overall feasibility and sustainability of OAWE systems and to supply recommendations for a sustainability-aware technology shaping. To achieve this, the project is structured around several core objectives:

1. **Farm Design**: This involves the development of an optimized layout and technical configuration for the offshore airborne wind farm, ensuring efficient energy capture.

2. **Techno-Economic Analysis**: This analysis assesses the economic feasibility of the OAWE project, including an evaluation of capital expenditures, operational costs, and the potential revenue streams from energy generation.

3. **Environmental Impact Assessment**: This evaluation analyses the potential environmental effects of the OAWE system, focusing on emissions release, resource use and ecological effects. The goal is to ensure that the envisaged system contributes positively to climate change mitigation efforts.

4. **Social Acceptance**: This investigation will evaluate the social impact assessment of OAWE deployment on local communities. The analysis will ensure that any negative impacts on communities are recognised, aligning the OAWE development with principles of social responsibility and inclusivity.

By combining the design and these three assessments, the project aims to establish a benchmark for future OAWE systems deployment, providing a comprehensive framework on environmental, social and economic aspects of the technology.

Understanding the problem

An Airborne Wind Energy system generates electricity using an automated flying device, typically a kite, which is connected to a ground station by a tether. There are two main approaches for electricity generation in such systems: the ground-generation method with the so-called pumping approach and the *flygen* method.
This last involves a rigid wing equipped with on-board generators. As the wing flies, it directly generates electricity, which is then transmitted to the ground via the tether.
This study focuses on Airborne Wind Energy systems functioning with the so-called pumping approach. In these types of systems, the energy is produced during a reel-out phase of the tether, while it is consumed during the reel-in phase. The core idea is that if the kite trajectory is suitably controlled, making the kite following a figure-eight pattern, the energy produced during the reel-out phase exceeds the energy needed in the reel-in phase, with an overall net energy generation in a cycle. The mechanical energy generated is then converted into electrical energy at the ground station. The ground station may include a generator and other equipment needed to convert the mechanical energy from the tether into electrical energy, like an energy converter and a battery module.
The term Offshore Airborne Wind Energy system refers to the offshore deployment of technology, where the system lays on a floating or bottom-fixed structure (figure 1). The former solution clearly requires the presence of mooring systems and properly shaped ballasts for an appropriate balance. Additionally, multiple offshore airborne wind energy systems may be strategically deployed to create a coordinated network, designed to operate collectively for optimal energy generation. So far, OAWE farms have only been theorized, with many optimistic claims in terms of their overall sustainability; however, no studies have been conducted to support or refute those claims.
Given the absence of OAWE farm projects so far, a preliminary **design phase** is necessary to characterize the farm. Specifically, we focused on the aircraft, the tether, the floating platform, the mooring system, the electrical machine and the transmission lines. Unlike an AWE system, there was a need for scaling the nominal power from the order of kW to MW to justify offshore deployment.
While an economic model is already available for onshore AWE systems, no study has been conducted to assess the **economic feasibility for offshore implementations**. It becomes necessary, therefore, to integrate the additional subcomponents required for an offshore setup.
Once the OAWE system is deemed feasible from an economic perspective, it becomes crucial to assess the environmental impacts. This ensures that the scaling of the components not only justifies the investment but also addresses the ecological challenges associated with such a transition.
Literature on environmental sustainability assessment of AWE systems is rather scarce, and to date, no studies have been conducted specifically addressing the aspects related to OAWE systems. Studying environmental sustainability is essential to understand the **ecological impacts** of new energy technologies. As demand for renewable energy rises, assessing the sustainability of AWE systems, especially OAWE, helps identifying strategies to mitigate negative effects. This knowledge supports informed policymaking and fosters innovation in sustainable energy solutions.
In addition to environmental and economic considerations, the literature on AWE systems lacks social acceptance studies, with only one on-field investigation conducted so far. When it comes to the offshore deployment of the technology, this deficiency even intensifies, with no studies ever conducted in the field.

However, with the AWE industry expected to be pushing the offshore deployment of the technology in the following years, the **inclusion of the population** in this transition will play a major role. This would not only lead to significant benefits in terms of sustainability, for a more socially just and heartfelt energy transition, but also from an economical point of view. Fighting the opposition once the technology has already occupied a solid market share would indeed imply higher deployment and project development costs than anticipating this same activity while still in the technology-shaping phase.

Exploring the opportunities

OAWE holds significant potential due to its unique characteristics. Economically, one of the key advantages of OAWE is its ability to achieve a higher capacity factor compared to traditional offshore wind farms. By harnessing stronger and more consistent winds at higher altitudes, OAWE systems are expected to generate more energy, leading to a **shorter payback period**. However, the offshore setup requires additional infrastructure, such as mooring lines and platforms, thus incurring **higher initial capital costs**. Despite these higher upfront expenses, OAWE systems tend to use **fewer materials** with respect to offshore traditional wind turbines—since they do not rely on large turbines or towers—thereby reducing manufacturing and installation costs. This leaner material requirement not only has the potential to lower overall costs but also contributes to a more sustainable, resource-efficient energy solution.

From an environmental perspective, the reduced material exploitation directly correlates with **lower environmental impacts**. Fewer resources used in construction mean a smaller carbon footprint, fewer emissions during manufacturing, and less waste over the system's lifecycle. Moreover, the absence of large stationary turbines minimizes disruption to both marine ecosystems and local wildlife, addressing some of the environmental concerns typically associated with offshore wind farms. This combination of reduced material use, economic viability, and lower environmental footprint positions OAWE as a potential competitive and sustainable option in the renewable energy market. Another significant opportunity for OAWE systems lies in their potential to **gain social acceptance**. This is supported by several advantages, often highlighted in the literature, such as their reduced visual and noise impact, with their design and placement minimizing disturbances; enhanced perceived safety, as these systems are seen as less intrusive and pose fewer risks to surrounding areas; and a lower environmental footprint, given their gentler impact on ecosystems compared to traditional wind turbines.

Generating a solution

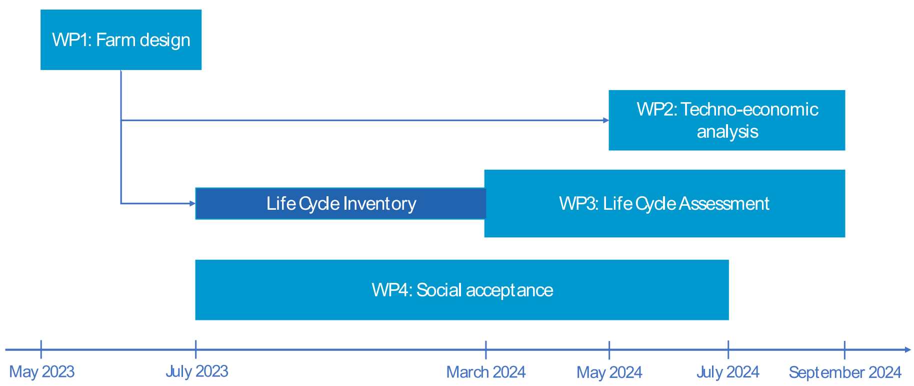

Figure 3: Project time planning

Farm Design

Having scaled the nominal power from the order of kW of an AWE system to MW for the offshore deployment of the technology, both the tether and the kite have been scaled to guarantee the new power values.

Regarding the floating platform, a boundary element code, NEMOH, has been used for evaluating hydrodynamic characteristics, and a frequency analysis has been performed to choose the proper mass depending on waves altitude and period.

Mooring lines and anchors, differently, have been designed with a low fidelity approach, without considering dynamic loads and fatigue.

A Permanent Magnet Synchronous Generator was designed based on geometric considerations, using its rated power and nominal speed as starting parameters.

The generated electricity is stored in batteries, which were specifically engineered to withstand the most demanding operational conditions, where all OAWE systems composing the farm are in their reel-in phase. The energy produced by the farm is transmitted via a network of AC, High Voltage DC, and High Voltage AC cables, strategically connecting various components based on the application. An optimization routine was employed to determine the most efficient cable layout. Based on the outcomes from the farm design, it is possible to evaluate its potentialities from environmental, economic, and social perspectives.

Sustainability assessment

The sustainability assessment has been performed focusing on the key dimensions economic, environmental and social using the following techniques:

- **Techno-Economic Analysis.** The techno-economic analysis exploited an open-source economic model specific to onshore Airborne Wind Energy. Capital expenditures and operational expenditures were adapted to evaluate the economic viability of deploying an offshore implementation, also including the required floating platform and mooring lines. Key financial metrics like the Levelized Cost of Energy (LCOE), Initial Capital Costs (ICC), Operational and Maintenance Costs (OMC), Net Present Value (NPV) and payback periods have been calculated and discussed, to clearly understand whether this innovative technology can compete economically with other renewable energy sources. The Techno-Economic analysis demonstrated that OAWE systems offer considerable economic advantages. The Levelized Cost of Energy for the offshore structure is **93EUR/MWh**, that is competitive with respect to the traditional wind turbine technology. The offshore AWE exhibits also a short **payback period, of only 4 years**. A highly **positive Net Present Value** and an **Internal Rate of Return of 28.4%** further underscore the offshore system's performance. However, these benefits come with **high ICC (1497 k€) and OMC (186 k€/year)**, whose distributions are shown in figure 4.

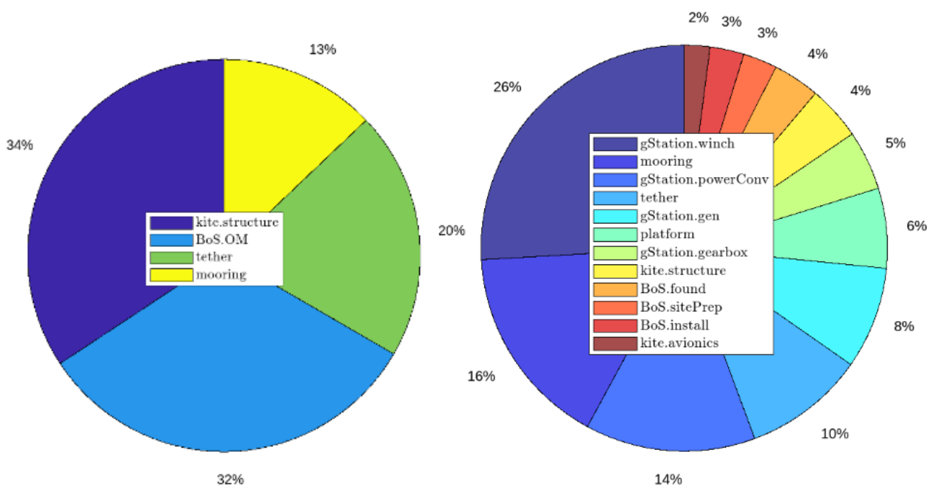

Figure 4: ICC distribution (on the right) and OMC distribution (on the left)

- **Environmental Impact Assessment.** The environmental impacts of the OAWE farm have been evaluated through the **Life Cycle Assessment (LCA)** methodology, a comprehensive tool that analyses various impact categories of the system thorough its entire life cycle, including extraction of raw materials, manufacturing and transportation, assembly and installation, operation and maintenance, decommissioning and disposal. The study aimed to quantify environmental metrics, according to the Environmental Footprint method, following ISO standards (ISO 14040 and 14044). Moreover, the most critical components have been identified, and results have been compared with traditional offshore wind energy solutions.
  The LCA highlighted that life cycle hotspots are the generators life cycle and the mooring lines life cycle. Moreover, the study revealed that OAWE systems exhibit an environmental footprint of the same order of magnitude as traditional offshore wind turbines, precisely showing **lower climate change impact** (**24.3 tons$CO_{2,eq}$/GWh vs 31.3 tons$CO_{2,eq}$/GWh**) and **resource use** (**0.26 kgSb_{eq}/GWh vs 1.71 kgSb_{eq}/GWh**).

The lower material requirements for the airborne structure, in fact, is key for positioning OAWE as a competitive and sustainable alternative for future energy production. Additionally, promising payback indices have been found, such as a **Carbon Pay Back Time (CPBT) of 1.5 years** and an **Energy Pay Back Time (EPBT) of 3.3 years**, over the farm life span of 30 years.

Figure 5: Impact assessment results in terms of contribution analysis for the OAWE farm

- **Social Acceptance.** The social acceptance analysis has been conducted through surveys and interviews, to highlight any concerns influencing public opinion, like visual impact, noise annoyance, safety risks or potential harm to marine life and ocean pollution.
  Results highlighted that the greatest concerns for the local population regard the **impacts on ocean pollution** and marine life for OAWE systems. Additionally, a modest worry about the visual impact of a hypothetical OAWE farm off the coast was recorded, specifically on the impact on the scenic view and the distance from the coastline. Recommendations for developers and the scientific community that is investigating OAWE systems are extracted from the results of the study. Given the level of concern towards the oceanic ecosystem, further investigations into the environmental impact of OAWE shall be conducted. Correspondingly, developers and local institutions are encouraged to properly **communicate these results** to the local population. By providing transparent information on the technology's benefits, developers can even foster trust in local stakeholders. Additionally, preventive and **bilateral communication** (*e.g.*, informative events) is strongly recommended to prevent opposition rather than confront it.

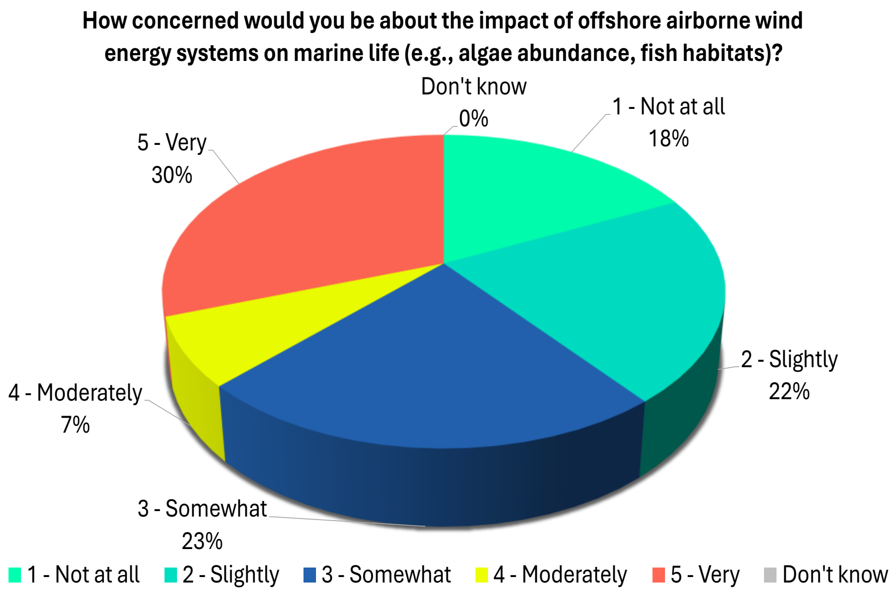

Figure 6: Pie chart showing the percentage of the recorded impact on marine life

Main bibliographic references

G. Brussa, M. Grosso, and L. Rigamonti. “Life Cycle Assessment of a Floating Offshore Wind Farm in Italy”. In: Sustainable Production and Consumption 39 (2023).

A. Campanile, V. Piscopo, and A. Scamardella. “Mooring Design and Selection for Floating Offshore Wind Turbines on Intermediate and Deep Water Depths”. In: Ocean Engineering 148 (2018), pp. 349–360.

A. Cherubini, R. Vertechy, and M. Fontana. “Simplified Model of Offshore Airborne Wind Energy Converters”. In: Renewable Energy 88 (2016), pp. 465–473.

R. Joshi and F. Trevisi. “Reference Economic Model for Airborne Wind Energy Systems.” Version 1. 2024.

H. Schmidt, G. de Vries, R. J. Renes, and R. Schmehl. “The Social Acceptance of Airborne Wind Energy: A Literature Review”. In: Energies 15.4 (2022).