Life-Cycle Assessment of an Airborne Wind Energy System

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List of abbreviations

AEP	Annual Energy Production
AWE(S)	Airborne Wind Energy (System)
CED	Cumulative Energy Demand
CFRP	Carbon Fibre Reinforced Polymers
EOL	End of Life
EPBT	Energy payback time
GFRP	Glass Fibre Reinforced Polymers
GWP	Global Warming Potential
HAWT	Horizontal Axis Wind Turbine
LCA	Life Cycle Assessment
LLA	Launch and Landing Apparatus
PGA	Power Generation Apparatus (also: AWE ground-station)
UHMWPE	Ultra-High Molecular Weight Polyethylene

1 Background

The Interreg North-West Europe project MegaAWE[1] aims "*to make accessible untapped wind resources by readying North-West Europe for the development and commercial prototype demonstration of utility-scale Airborne Wind Energy Systems, with unique benefits over conventional Horizontal-Axis Wind Turbine technology.*" The project started in 2020 and lasts until 2023.

This paper represents a deliverable which is defined as "*life-cycle assessment to quantify MW-AWES footprint benefits to support policy action*". It is based on graduation project and MSc thesis carried out at TU Delft and which had been commissioned for this purpose in cooperation with Ampyx Power and Airborne Wind Europe.[2]

2 Objective

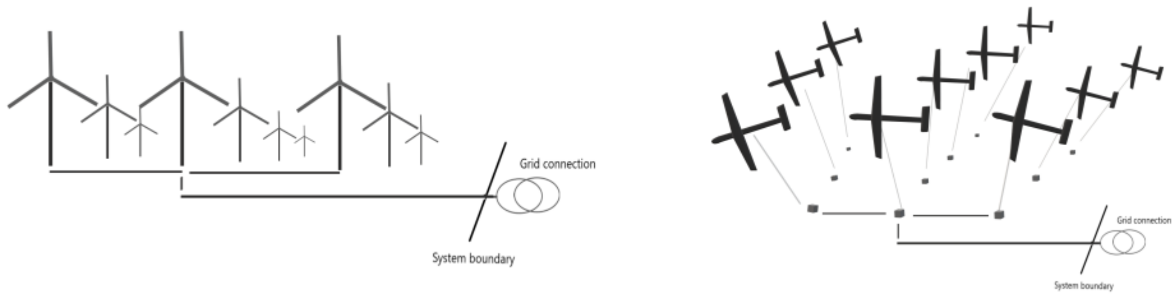
The goal of this research is to assess the environmental performance of a future multi-megawatt Airborne Wind Energy (AWE) system by quantifying its Global Warming Potential and material intensity, and by comparing them with the impacts of a Horizontal Axis Wind Turbine (HAWT) system.

Moreover, the Life-Cycle Assessment (LCA) aims to contribute to using more sustainable materials in the early design processes of AWE systems and to raising awareness on circular economy aspects in the AWE sector. Finally, the LCA is meant to provide data and information on the impacts of AWE technology to the scientific community, stakeholders in the wind and renewable energy sector as well as to policy makers and the public.

3 Scope and Assumptions

The LCA study compares two 5 MW systems: A hypothetical commercial fixed-wing AWE system and a 5 MW reference HAWT based on the reference HAWT from NREL.

The systems are compared at an onshore location within a hypothetical wind farm of ten units totalling 50 MW with the same farm lay-out, i.e., the same distances between single systems and farm distance to the main grid.



(a) HAWT farm   (b) AWE farm

Figure 1: Visualisations of the 50 MW farms and the considered system boundaries. (Van Hagen 2021)

The AWE system is based on the design of the Ampyx AP3, a 150kW system that is currently being tested in the Netherlands and from mid-2022 onwards at the new test site in County Mayo in Ireland.

[1] MegaAWE - Maturing utility-scale Airborne Wind Energy towards commercialization | Interreg NWE (nweurope.eu)

[2] Van Hagen, L. (2021)

Two AP3 airborne devices are shown in Figure 2 below:

Figure 2: Two "AP-3" aircraft at Ampyx Power headquarters in May 2021

The Ampyx system uses a catapult to launch the aircraft and it uses a so-called shifter system to decelerate the system when landing on the platform, see Figure 3:

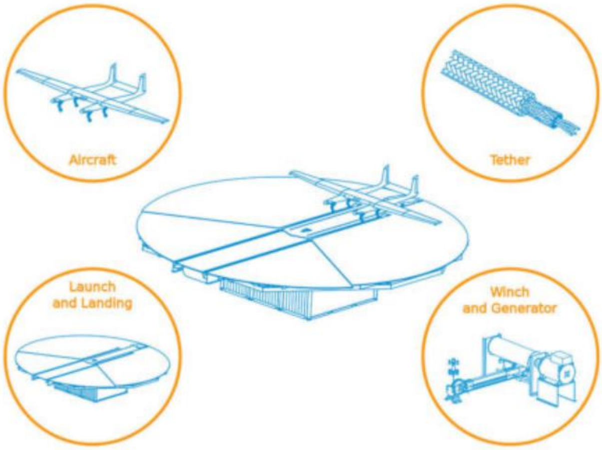


Figure 3: Components of Ampyx' AWE system (Ampyx Power).

These components are thus specific to Ampyx' AWE system design, therefore they cannot be considered representative for other AWE concepts which may use either different launch & land systems (like rotating arms or masts) or do not require a specific apparatus at all like the AWE aircraft that feature vertical take-off and landing (VTOL) capability.

This also applies for the accumulator system which may be solved differently in other system designs. In that regards the Ampyx ground station components can be considered as being potentially heavier than the ones of other OEMs that use a fixed-wing concept.

Several assumptions for the 5 MW AWE system have been made for this study as scaling of the AP-3 prototype cannot be made by extrapolation alone. While some key principles are expected to remain the same, assumptions on technological choices (e.g. drivetrain, launch and land system, component lifetimes), mass (e.g. airframe) and performance had to be made.

Furthermore, it is assumed that the bottom 300m of the tether, i.e. its thicker, lower part of the tether which is winding around the drum, is replaced on an annual basis, while the rest of the tether is replaced three times within the 20 years of service life.

Table 1 summarizes key assumptions for the base-case.

Table 1: Base-case specifications (Van Hagen 2021)

Spec	AWE	HAWT
Location	Onshore	
Farm size	50MW, 10 Units	
Service life	20 years	
Capacity factor	52,80% at:	46,90% at:
At avg wind speed of	11m/s	10m/s
Specifications	Ground-gen, Rigid wing	IEC1 rated
Wing span / Rotor diameter	53.7m	126m
Avg flight / hub height	250m	117m
Tether length	1200m	
Tether / Tower	Single, 2 sections	Steel cylinder
Drivetrain	Hydraulic	DFIG

4 Key Findings of the LCA

4.1 The normalized mass of the AWE system is 70% lower than the one of HAWT

The analysis found that AWE require significantly less material than HAWT to produce the same amount of electricity. The normalized material mass during the 20-year lifetime of the AWE system is 30% compared to HAWT (2.0 vs. 6.6 kg/MWh). This includes replacements such as tethers, actuators, and batteries. The total, non-normalised mass of the AWE system is about 32% of the HAWT mass (913 vs. 2868 metric tons).

As can be seen in Figure 4, this difference is mainly due to the tower and the foundation:

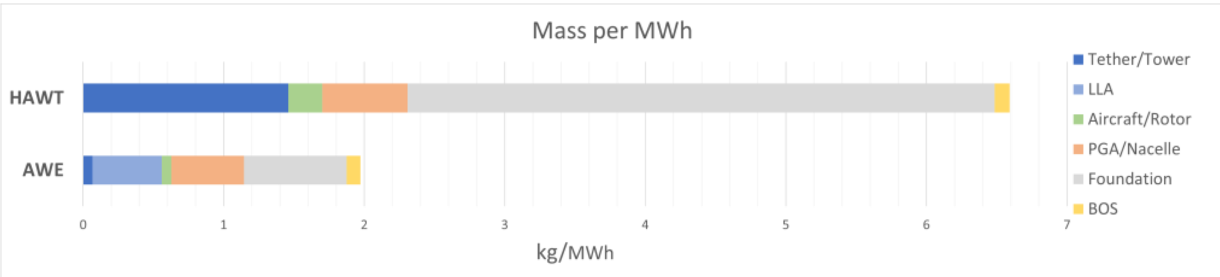


Figure 4: Mass comparison AWE vs. HAWT (Van Hagen 2021)

The foundation of the AWES is about 80% lighter than that of the HAWT system. The tower is replaced by the tether and the launch & land platform. The aircraft is also lighter than the rotors while the ground station is heavier than the HAWT nacelle. As it can be seen, the launch & land apparatus together with its foundation contribute considerably to the overall weight of the AWE system (together about 60%).

The masses of the AWE system components are further detailed in Figure 5:

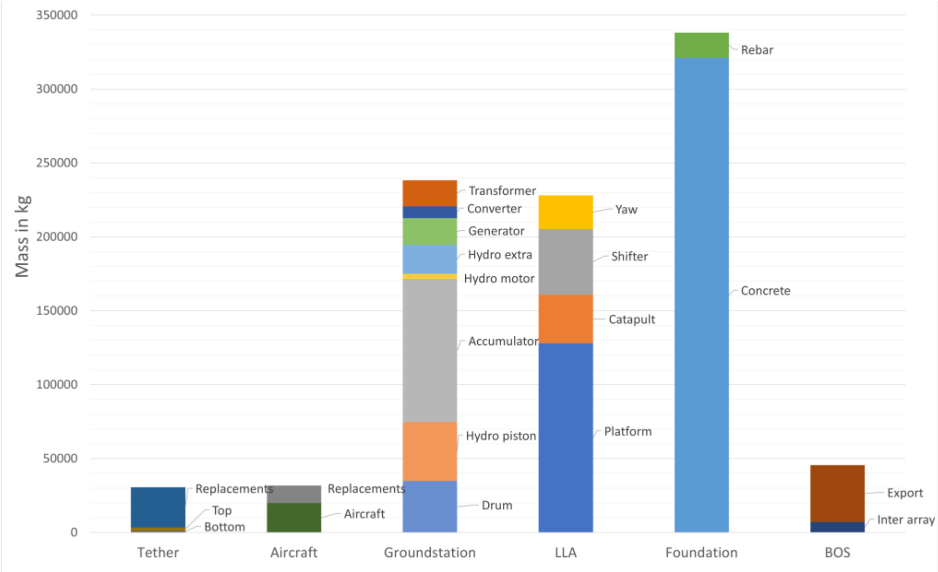


Figure 5: Masses of the AWE system, including replacements (Van Hagen 2021)

In this mass analysis, the following point should be highlighted: The circular economy concept is based on the 'reduce – reuse – recycle' approach. Even though wind turbine manufacturers aim to reduce the specific mass of their systems, it is hardly conceivable that it will be possible to achieve mass reductions of some 70%. This step change nevertheless is possible with a completely different concept such as AWE.

4.2 The Global Warming Potential (GWP) of the AWE system is 40% lower

A reduced need for materials is already positive by itself because it reduces the pressure on available resources like steel, sand, etc.[3], However, when it comes to the relevance for the climate, the *type* of material used is of higher importance. For that reason, two commonly used indicators have been calculated: the Global Warming Potential (GWP) and the Cumulated Energy Demand (CED).

Given that AWE requires energy-intensive components like the tether and the aircraft, the GWP advantage of AWES is not directly linear with the mass. Therefore, the comparison is normalized to the electricity that is produced. The AWES' GWP is in this comparison 40% lower than the one of the HAWT system (7.80 vs. 13.0 $kgCO_{2eq}$/MWh), see Figure 6.

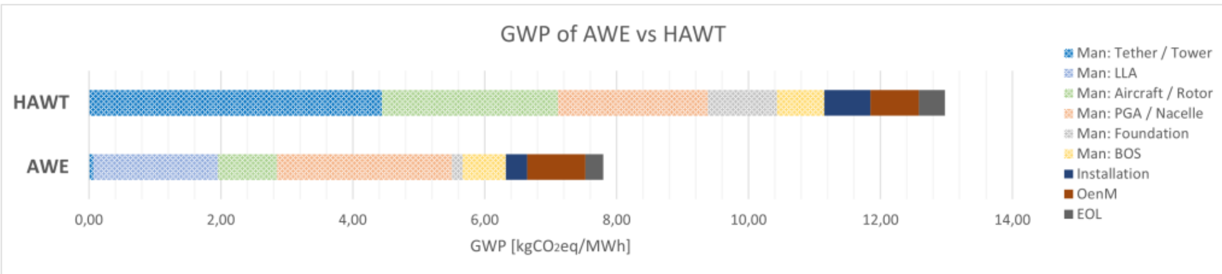


Figure 6: GWP of AWE vs. HAWT[4] (Van Hagen 2021)

[3] The LCA indicator "abiotic depletion" was not in scope of this study, but it would be interesting to include it in future LCA work.

[4] The dotted-filled bars represent the materials and manufacturing stage split into the 6 subsystems. Impacts of the replacements (e.g. tether) are included in the O&M stage.

With regards to the Cumulated Energy Demand, the AWE system requires 35% less energy input to generate one MWh of electricity compared to the HAWT system (127.5 vs. 195.0 MJ/MWh), see Figure 7:

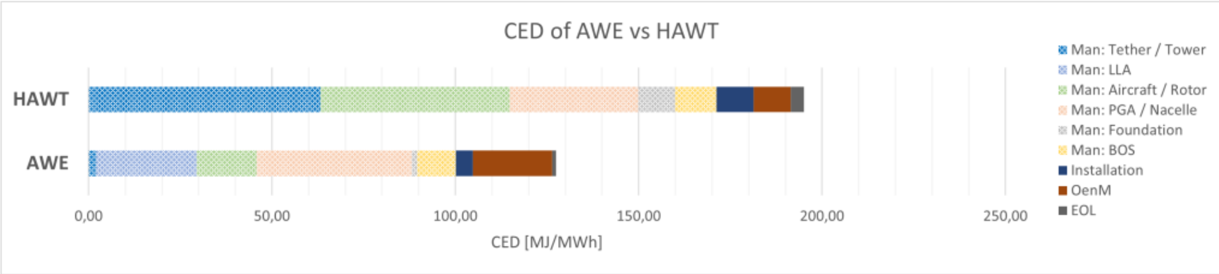


Figure 7: CED of AWE vs. HAWT (Van Hagen 2021).

These values can be translated into the **Energy Payback Time** (EPBT) which states how long it takes for a system to produce the amount of energy that was required to build and run it. The EPBT of the AWE system requires 8.5 months whereas the HAWT system needs 13 months to pay back all input energy.

The **Energy Return on Investment** states how many times the energy input is returned as output over the service life of a system. The AWE system will generate 28.2 times its input energy while it is 18.5 times for the HAWT system.

4.3 Four key AWE components have greatest impacts

The Life-Cycle Stage "Materials and manufacturing" has the highest environmental impact on GWP and CED: As can be seen in Figure 8, for AWE these Life Cycle Stages account for about 81% of GWP (78% of CED) while for HAWT it is 86% of GWP (88% of CED).

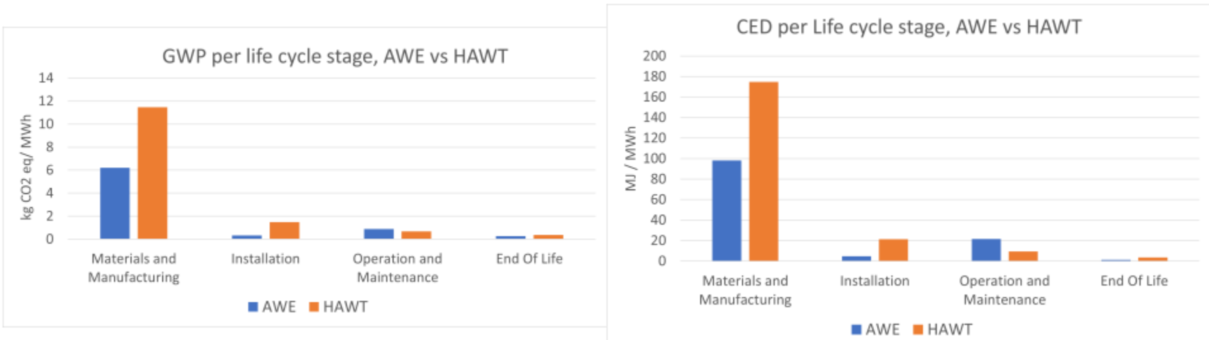


Figure 8: GWP and CED per Life Cycle Stage of AWE vs. HAWT (Van Hagen 2021)

The O&M impact on GPW and CED is higher for AWES compared to HAWT - both in absolute as in relative terms, especially due to the regular substitution of the tether which accounts for about 60% of the O&M impacts.

Looking more closely into materials and manufacturing, four "hotspot" components show the highest impacts on GWP and CED: the tether, the aircraft, the launch & land apparatus and the accumulator system, see Figure 9.

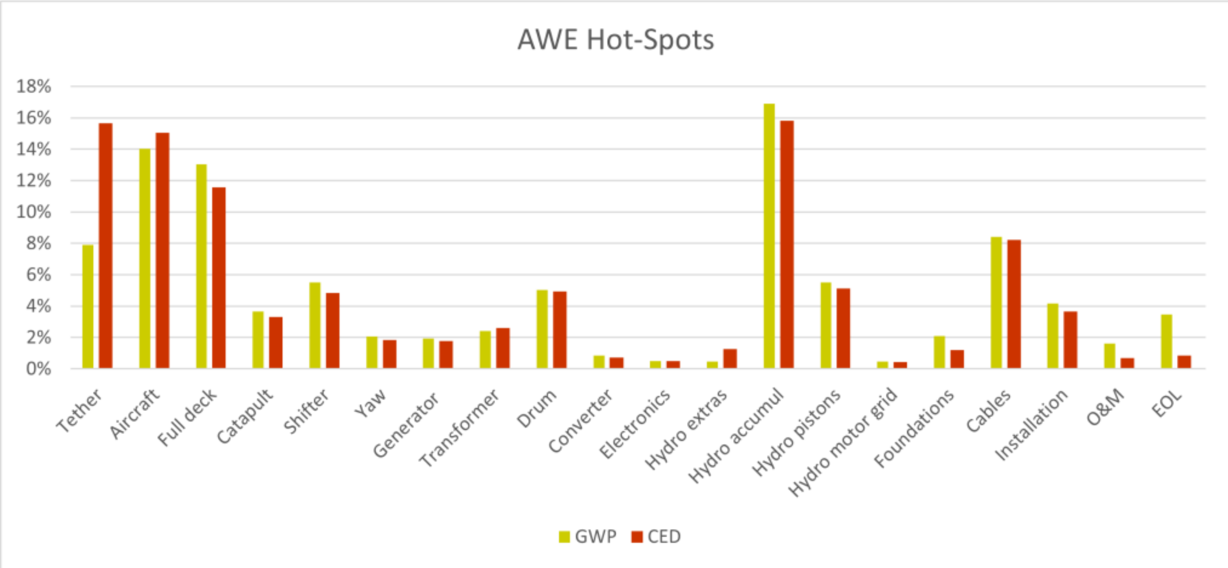


Figure 9: AWE hotspots (Van Hagen 2021)

The tether has only a 1% share of the GWP but due to the replacement, it adds up to 8% over the lifetime of the system. The CED share is even close to 16% due energy intensive production process of the material Ultra High Molecular Weight Polyethylene (UHMWPE). It is assumed that the tethers are produced also in future with a high share of renewable electricity as it is already currently the case; this explains the difference between percentage values of GWP and CED.

The aircraft contributes 14% to the GWP. More than half of this value are due to the use of Carbon Fibre Reinforced Polymers (CFRP). This material is more energy intensive than e.g. Glass Fibre Reinforced Polymers (GFRP) which is used in HAWT blades.[5] It should be noted that the mass of the aircraft is a crucial factor as it not only affects the GWP impact of the aircraft itself but also the size and mass of the launch & landing system as well as the flight behaviour and therefore the whole energy output of the system.

The Launch & Land apparatus including deck, catapult, shifter and yaw system accounts for about a 25% of the GWP impact; however, as mentioned above, the data for design, material and mass of the deck are based on uncertain assumptions and may significantly change in future.

The accumulator system is part of the ground station (or "Power Generation Apparatus") and responsible for about 17% of the GWP. This system stores energy in a combination of hydraulic piston accumulators and additional nitrogen pressure vessels in order to produce a constant electrical power output. The contribution to the GWP is due to the high mass; the hydraulic piston accumulators alone weigh 48 tons.[6]

4.4 AWE is especially advantageous in low-wind onshore and floating offshore locations

For a number of design choices and input factors **a sensitivity analysis was carried out**, mostly varying parameters by 20% up and downwards: AWE aircraft mass, share of GFRP in blades, distance to grid, capacity factors, total system life-time, tether life-time, AWE system size, as well as HAWT tower height and mass in combination with the location.

The sensitivity analysis showed under almost all scenarios **lower GWP and CED values for AWE than for HAWT**, even for quite extreme scenarios. The advantages are less prominent in locations where HAWT do not require high towers like in shallow offshore locations and onshore with low surface roughness. By contrast, in locations where masses for HAWT increase due to higher hub heights like in low-wind onshore

[5] The HAWT blade was modelled with 50% CFRP and 50% GFRP. The bigger the blades, the more likely is a higher share of CFRP.

[6] The accumulator system was not included in the LCA carried out in 2015 (Wilhelm 2015) which explains in part the more favourable GWP and CED values in that study; also tether, foundation and aircraft were considered lighter, off-setting the higher capacity factor and lower tether impact found in the present LCA study.

locations or like in deep-offshore locations (where floating systems are required), AWE systems show up to 47% lower GWP values.[7]

4.5 Uncertainties regarding assumptions and up-scaling remain

Choice of assumptions: The modelled AWE system of 5 MW is still several design iterations away from the currently built AP3 system with some 150 kW. The assumptions used are based on a mixture of upscaling and improved system design. Therefore, the design and data uncertainty is quite large compared to the HAWT.

Scaling-up of AWE systems not necessarily beneficial: The AWE model used in the analyse seems to indicate that the masses of components like aircraft, launch & land apparatus and tether scale faster than the rated power of the system. This could mean that AWE systems smaller than 5 MW may be more beneficial, and further upscaling may be counterproductive. However, given that there are still no real demonstrators with system sizes in the MW-range, drawing such a conclusion would be premature. Further AWE development and research will therefore be required to properly assess if and under which circumstances there is an optimal size for AWE systems or not.

5 Conclusions and recommendations

5.1 AWE represents a step-change towards a Circular Economy

The Circular Economy approach aims at the continuous use of resources in a closed-loop system to minimise the input of resources and the creation of waste. It suggests rethinking the way industry and society produces and consumes products and resources in order to reduce, reuse, repair and recycle all materials.

AWE consequently applies the 'reduce' rule which is one of the most valuable Circular Economy options. Offering a significant mass reduction for energy generation from wind, AWE represents a step-change and fundamental re-design of wind energy technology.

Certainly, the actual mass reduction of AWE vs. HAWT will strongly depend on the AWE type and further developments, and material input will always be required. Therefore, it is also important to further investigate how materials can be reused, how system components can be easily repaired and which materials can and should be used considering their recycling potential. Further research is also required to identify business models that incorporate the circular economy approach; for instance, a tether may not be sold to the system operator but rather rented out, applying a revenue model that is based on ‘energy transferred from the kite to the ground station’ rather than on ‘meters of tether sold’. That way the tether will be optimised to extend its lifetime.

The LCA study has been carried out with a **cradle-to-grave approach** which means that while recyclable materials are defined to be recycled, the avoided impacts of recycling are not credited to the assessed systems. There are large uncertainties regarding recyclability and rate of usage of recycled materials for most materials, especially for the Carbon Fibre Reinforced Polymers and Ultra-High Molecular Weight Polyethylene. Further research is required to identify materials that can be ideally reused (instead of being down-cycled) for the same application. Applying the so-called Material Circularity Indicator in future LCAs may provide further insights.

5.2 AWE OEMs can benefit from LCAs in system design

During the elaboration of this LCA, the feedback loops with Ampyx Power proved to be important, especially with regards to the calculations on the potential future design of a 5 MW system. This process may have already triggered some re-design decisions for the next prototype that is being developed. By conducting LCAs for their own systems, **OEMs will be able to make more data-based decisions,**

[7] It should be noted that a detailed floating offshore setup was not modelled neither for AWE nor for HAWT due to lack of data and resources but some rough estimations were performed.

preventing lock-ins at later development stages. Even though an LCA requires substantial efforts from the participating companies, it can be most beneficial and informative for the design teams in an early stage of development.

For instance, initial calculations on the weight of upscaled system components showed how important design choices are when it comes to reducing environmental impacts. Reducing the aircraft mass through the use of Carbon Fibres will not only reduce the impacts of the aircraft but also reduce the required mass of the launch & land system. However, these advantages need to be balanced against the potential disadvantages of using Carbon Fibres which – at least as of today – have a higher Global Warming Potential.

5.3 LCAs for different AWE concepts are needed

The modelled 5MW rigid wing AWE systems was chosen to compare against a typical HAWT. Comparing AWE against HAWT will also in future be a valuable and important exercise – especially when more real-life data of AWE systems become available – because both systems provide mutual benchmarks to each other.

Apart from that, **LCA comparisons between different AWE system concepts** should also be performed, for instance ground-gen vs. fly-gen, fixed-wing vs. soft-wing, or similar systems with different launch and land concepts (catapult, vertical take-off and landing, masts, rotating arms, etc.). Depending on the system choice, the impacts on GWP and CED may differ greatly.

Such a comparison between AWE concepts should already be carried out with the systems that are currently developed, i.e. **for systems in the few hundred kW range**, because data are more accurate than the ones of the scaled-up, hypothetical system used in this LCA. Future LCAs may also **include other indicators for environmental impacts** which have not been in scope of the LCA, such as ozone layer depletion, human toxicity, acidification, abiotic depletion, eutrophication, or the above-mentioned Material Circularity Indicator.

5.4 Policy makers to acknowledge the potential of AWE

Current wind energy technology is already one of the electricity generating technologies with least environmental impact. Notwithstanding the lack of detailed design data and assumptions, **this LCA concluded that AWE systems have an even lower environmental impacts in terms of GWP and CED compared to HAWT.** While HAWT efforts to further reduce weight and impacts need to continue, policy makers and industry should acknowledge that AWE provides a promising technology which can accelerate the transition towards ever more sustainable renewable energy solutions and become a complimentary technology to existing wind turbine systems.

However, **to reap the potential benefits of AWE, it requires a continued and scaled-up support** in terms of R&D funding (including further LCAs) but also in terms of facilitating the commercialisation and market-entry of AWE by adapting legislation, regulation and incentive schemes which are specifically designed for AWE systems.

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