Getting airborne – the need to realise the benefits of airborne wind energy for net zero

White Paper for Airborne Wind Europe

September 2022

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Abbreviations

AWE	Airborne wind energy
AWE-TD	AWE technology developers
DECEX	Decommissioning expenditure
DEVEX	Development expenditure
CAPEX	Capital expenditure
LCOE	Levelised cost of energy
OPEX	Operational expenditure
UAS	Unmanned aircraft systems
VTOL	Vertical take-off and landing
WACC	Weighted average cost of capital

Executive summary

Airborne wind energy (AWE) is wind 2.0 – a game-changing solution accessing the large untapped wind resource potential at heights above those accessed by established wind technology. It enables more energy to be extracted at lower carbon intensity and eventually at lower cost.

Europe and other areas in the world need to access all viable natural resources they can, and AWE, alongside established wind technology, should be considered as one of the key solutions to our energy decarbonisation challenge.

Benefits of AWE

AWE is worth developing because:

AWE opens new areas for energy from wind

Europe and other areas in the world should benefit from all viable natural resources in their rapid move to net-zero electricity production and increasing their energy security of supply.

Europe currently has 207 GW of onshore wind capacity [i], and the European Commission has a vision for this to increase to 1,000 GW by 2050 as part of its net-zero vision. [ii] This means that many more wind sites need to be developed.

Many countries are already struggling to find enough viable sites for onshore wind, hence the move to developing offshore wind at scale.

AWE has a much lower logistics requirement than established wind technology, hence it can be installed in places that established wind cannot. Many of these are high-wind areas offering low LCOE.

AWE offers increased energy generated per square km

With Europe needing more energy production from wind, AWE can play an important role by using available space up to about three times more effectively.

This means AWE can deliver more energy on any given site. Proof of the precise improvement factor will come following practical experience operating multiple AWE projects, but it is likely to be significant.

This either reduces the need to use so many of the lower-wind (so higher LCOE) sites, or enables generation of more renewable energy.

If Europe used half AWE, half established wind technology, then it could get up to twice the energy production.

AWE has a higher capacity (load) factor than established wind technology on the same site with the same nominal capacity, with figures over 60% anticipated on sites with good wind resources. This means that (as for offshore wind), AWE is closer to acting as 'baseload' than established onshore wind technology or solar.

In time, AWE can provide energy at lower cost than established wind technology

In time, AWE can provide energy at lower cost than established wind technology

Although currently higher cost, with public investment in technology development, by the early 2030s AWE will be able to compete with an average price lower than established wind technology in the mid-2030s.

By also harvesting the larger wind resource potential at heights of 300 to 500 m, AWE will be viable on more sites that are not viable for established wind technology.

AWE offers more opportunity for efficiency improvement when making planned component changes and thus LCOE improvement during the operating life of projects.

AWE can also be seen as a hedge against commodity price and cost of money increases, decreasing the competitiveness of established wind technology, as it uses less material and has lower capital expenditure (CAPEX) investment than for established wind turbine projects.

i https://windeurope.org/intelligence-platform/product/wind-energy-in-europe-2021-statistics-and-the-outlook-for-2022-2026/

ii https://etipwind.eu/publications/getting-fit-for-55/

AWE offers a potentially more attractive investment opportunity, again due to lower CAPEX investment than for established wind turbine projects.

AWE has lower environmental impact

AWE has at least 40% lower carbon intensity than established wind technology, fundamentally because it uses much less material. Some concepts may achieve a reduction of up to 90% based on drastic reduction in material requirement.

Established wind technology (at about 10 kg/MWh) has much lower carbon intensity than fossil fuels (at about 500 kg/MWh), but as we look to net zero, even this intensity will be a challenge to offset.

The relative ease of installation for onshore and offshore AWE means decommissioning also has less local environmental impact than established wind turbines. Moreover, AWE can be a valid alternative to reuse offshore infrastructure instead of decommissioning it.

Route to volume market impact

We modelled a scenario of market growth of AWE systems to 2050, as shown in Figure 1. This was based on an understanding of realistic early sales forecasts of leading AWE technology developers (AWE-TDs).

Longer term market growth was based on the historic growth of established wind. This market growth was used to understand the potential for AWE's cost competitiveness.

Early Growth (2021-2026)

- The initial AWE market is likely to grow where established wind turbine technology is not viable, especially due to logistics. To get to significant volume, however, AWE needs to offer a competitive alternative to established wind turbines on a wide range of sites.
- AWE is expected to benefit from the understanding and processes developed for established wind technology, as well as aerospace/drones. For example, the industry is engaging with the processes of wind turbine type certification and aviation safety certification, to enable bankable projects.
- As with established wind, the needs for permitting at volume are expected to be addressed in parallel with the industry growing.
- The rate of early growth will depend on the bankability of the technology (including the role of certification), permitting (especially establishing regulatory frameworks including aviation-related regulation), and the time it takes to develop an onshore site (including securing revenue support). There is much that can be learnt from established wind to accelerate this.
- The rate of growth will also depend on how well the industry builds a healthy pipeline of sites needed for early years. This is a current focus for the industry.
- The first commercial 150 kW AWE single kite system was supplied by SkySails in 2021.
- At least four other companies are following with 50-150 kW devices expected to achieve installations in the period 2022 to 2025. Together the expected total cumulative market reaches over 90 MW by the end of 2026.

Longer term growth (2026-2050)

- We modelled a scenario based on assuming that the AWE market follows the same trend as the established wind turbine market, but 40 years later. The established wind turbine market from 1985-2010 is assumed for AWE from to 2025-2050. Though somewhat arbitrary, we have done this because the established wind turbine market is a real example of a pattern for growth. The modelled scenario shows 5 GW of AWE deployed by 2035 and 177 GW by 2050.
- AWE technology is expected to benefit from many markets already having renewable energy frameworks in place, a strong global pull for low-carbon solutions and a finance community that understands variable output renewables. This means that it has the potential for more rapid growth.

iii https://airbornewindeurope.org/megaawe_airbone-wind-energy-system-life-cycle-analysis_2021-09-29-2/

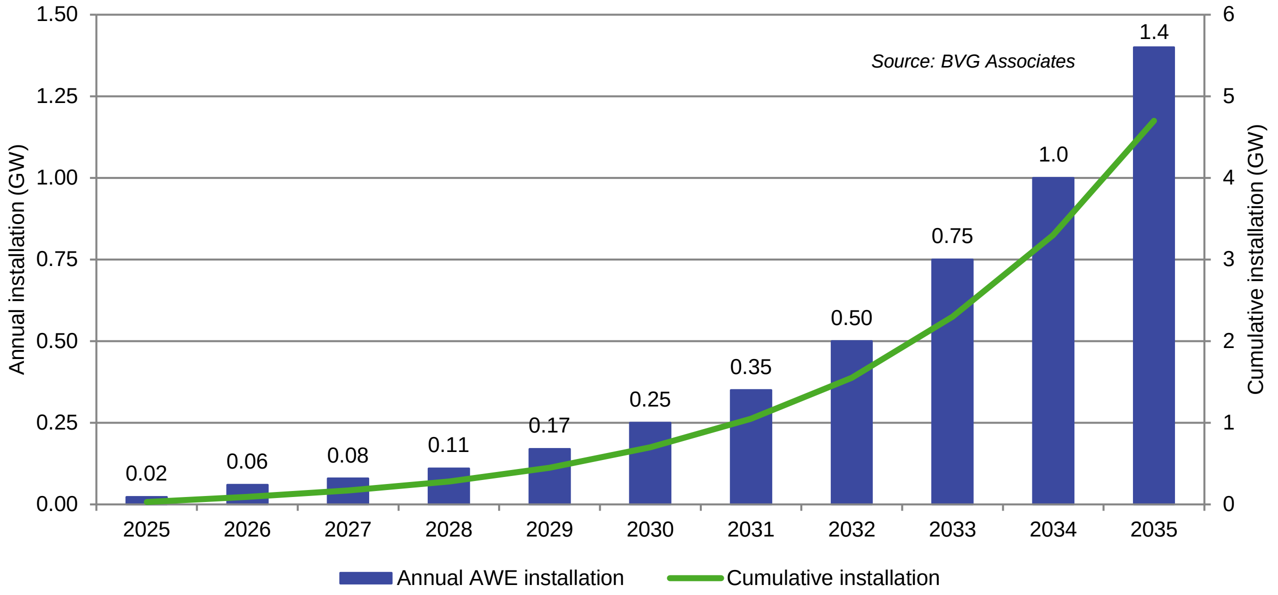


Figure 1 Global AWE initial installation from 2025 to end 2035.

Cost of energy

- We have modelled future LCOE trajectories for AWE and established wind technology on a like-for-like basis, as shown in Figure 2, from cost and energy production forecasts.
- We can have confidence in an eventual 40% lower LCOE, because mass and material cost for AWE already is 70% lower than for established wind technology, for a project producing the same amount of energy.
- Much of the future development is in technologies relevant to drones, unmanned aircraft systems (UAS) and low carbon aerial transport, with many synergies with tomorrow's industries.
- Installation of AWE devices is easier and quicker than established wind turbines. While finding sites may be a more complex task, the versatility of AWE installation should mitigate any challenge.

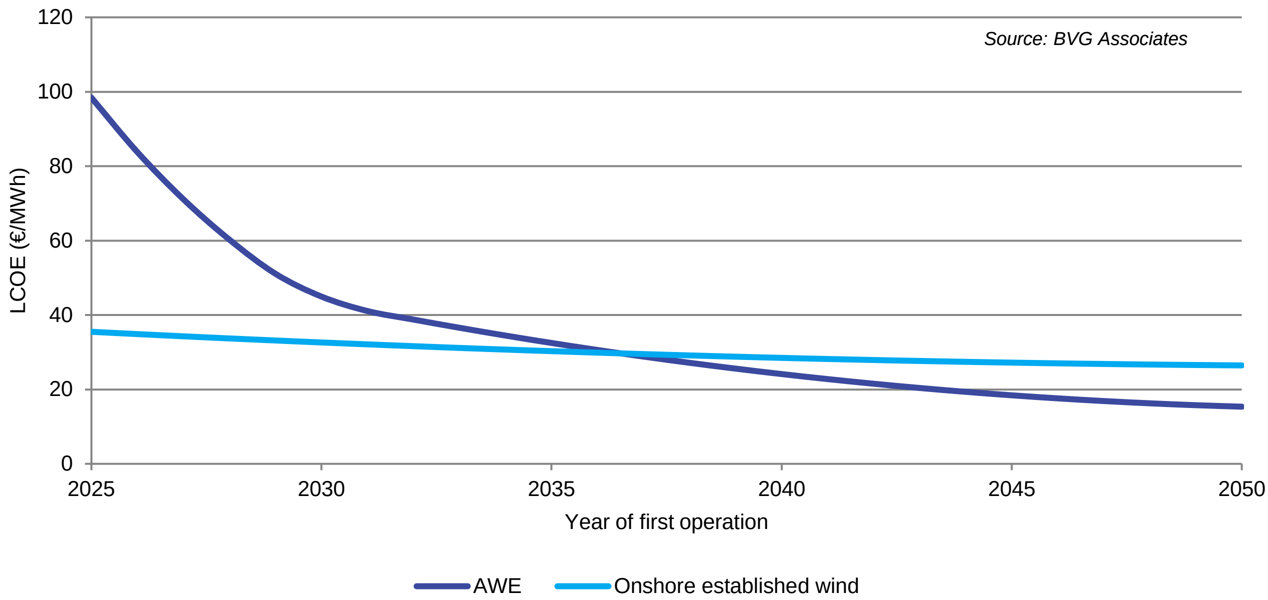


Figure 2 Trend in average LCOE of AWE and onshore wind turbine technology

The AWE sector ask

Public support of about €5 billion is needed, split as €4 billion for project electricity price support and €1 billion for industry development support.

As with all new energy technology:

- This ensures sufficient R&D happens
- Companies have the necessary stability to efficiently undertake the technology and product development
- Regulatory regimes are established
- The first commercial projects promptly go ahead
- The environment needed for AWE technology to be deployed at volume in existing markets is established, and
- AWE is able to properly develop to compete with established wind technology.

The €4 billion for project electricity price support estimate is derived from the relative cost of energy forecast for AWE compared with established wind. The cost of energy of AWE projects is forecast to break even with established wind technology in about 2036, as shown in Figure 2. Figure 3 shows the price difference on average between AWE and established wind, which reaches an annual peak of €0.45 billion per year in 2033. The extra cumulative cost to get AWE to the break-even point compared with the cost of established wind technology is shown to be about €4 billion, when just over 10 GW of AWE will have been installed. Most of this will need to come from public support. The net generation cost benefit of AWE over established wind technology by 2050 is more than €100 billion.

Given AWE is such a promising technology, with such potential to help in the fight against climate change, provision of support to accelerate its development is urgently needed.

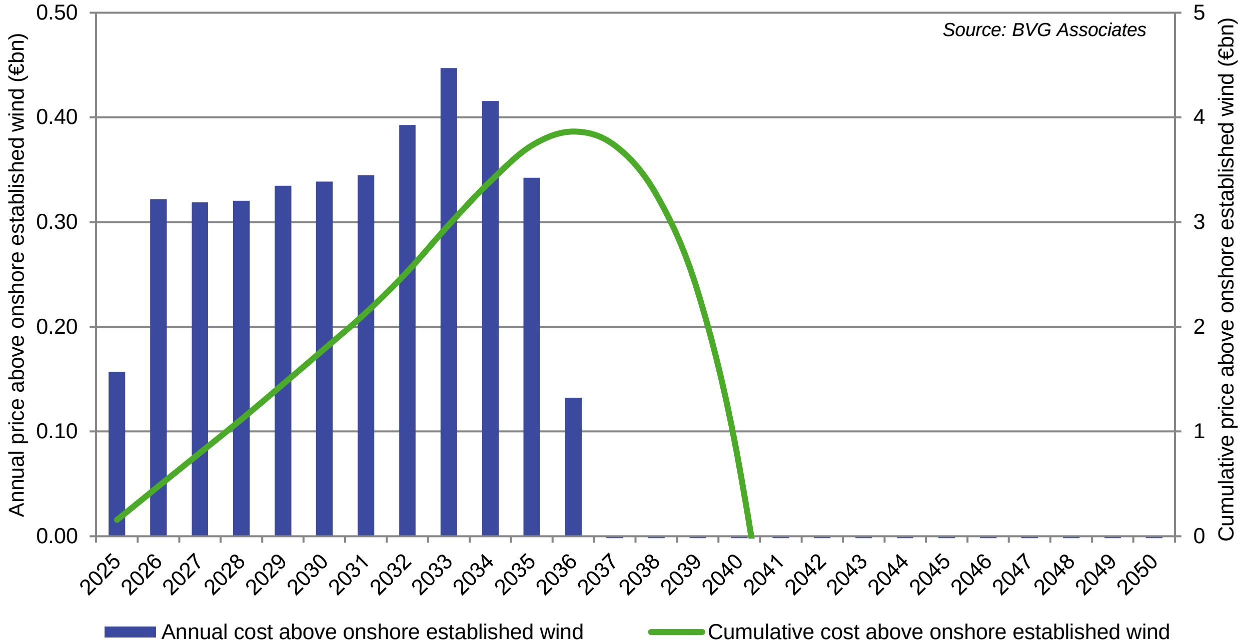


Figure 3 AWE cost in excess of that for established wind turbines.

1. Introduction

This report

This White Paper was commissioned by Airborne Wind Europe, the airborne wind energy (AWE) trade association, from BVG Associates to provide independent insight into the market potential of AWE technologies, AWE cost trends, and capture the energy market challenges.

This work was co-financed under the Interreg North West Europe programme MegaAWE.

Airborne wind energy

AWE offers the potential of providing another source of cost-effective renewable energy generation at scale in the fight against climate change. It has the potential to add significantly to energy production by established onshore and offshore wind technology.

AWE systems use autonomous tethered flying devices to harness energy from the wind. Most devices have ground-based powertrains where a generator is run by a tether being pulled out by the flying element, followed by reeling-in the device for another cycle (tether-gen). Other ground-based power systems use rotary motion (rotor-gen). Some concepts in development have onboard powertrains (fly-gen). There are many different forms of devices under development, and it is not clear whether any one solution will prove to be the best.

Given the potential contribution of AWE, it is important that the true capability of AWE to support the clean energy transition is determined quickly. Development of the most promising AWE technologies needs to be accelerated.

About 20 small companies, the majority of which are based in Europe, are developing devices, with some expecting to have commercially operational onshore systems by 2025. Like all small companies without significant revenue streams, they are vulnerable to uncertainties of funding, including research grants and raising venture capital. This limits the speed of technology development, and in some cases their ability to function properly as companies.

History

Airborne wind devices convert energy from the wind without being supported by a tower. They are tethered to a base station on the ground or to a fixed or floating platform for offshore applications.

AWE devices have been proposed since the 1970s, however the technology needed in materials and control has only emerged more recently, thus AWE is at the stage that established wind was about 40 years ago.

Over the last decade, the AWE sector has developed from conceptual ideas and the first small-scale experiments, to producing a diverse array of technology demonstrators ranging up to power outputs of hundreds of kilowatts.

About 20 AWE technology developers (AWE-TDs) are advancing technologies with over 50 research institutes, industrial associations, supply chain companies and utilities involved in the development ecosystem.

The main focus is on developing onshore devices. Offshore application of AWE is also being considered by many AWE-TDs, especially mounting devices on vessels now and on (bottom-fixed and floating) foundations in the future.

In 2019, Makani partnered with Shell to demonstrate the operation of a 600 kW kite prototype from a floating platform in the North Sea. [iv] In 2020, Makani's owners decided to stop development of their device as its technology had high risks and long development horizons. There has also been consolidation elsewhere in the industry, with a number of AWE-TDs not able to secure sufficient funding to take their technology to market.

Some AWE-TDs have started the process of commercialising their systems. Several others are planning to go to market within the next three years. The initial market is onshore, with the potential to move offshore once the technology is available at the right scale and is sufficiently mature.

iv https://x.company/projects/makani/
https://www.youtube.com/watch?v=lOXDuP-8Wdo

The challenge

The global energy system requires an urgent transition away from fossil fuels to avoid the worst impacts of climate change. While the progress to date of renewable energy technologies displacing traditional fossil generation is encouraging, more needs to be done and faster to retain the possibility of limiting warming to less than 2°C.

The speed and scale of the challenge means innovative technologies capable of offering the ability to generate renewable energy beyond existing technologies need to be sought and supported. While the contribution of AWE to decarbonisation up to 2030 will be relatively small, it could have a significant impact by 2040. As such, enabling a healthy innovation ecosystem for AWE development is crucial to determine the scale of the benefits that it can provide and to ensure that these benefits are realised quickly, to contribute to the transition from fossil fuels.

Contents of this white paper

Section 2 includes an overview of the main AWE technologies, whose benefits are then described in Section 3.

Section 4 describes the route to market and volume required to realising the benefits of AWE.

Section 5 presents maps of levelised cost of energy (LCOE) in 2030, 2040 and 2050 to show where AWE is likely to be most competitive. These show which onshore areas of the world that diesel, solar PV, established wind and AWE are forecast to have the lowest LCOE.

Although the main focus for AWE initially is onshore, it is expected in time to provide benefits for offshore wind, and this is discussed in Section 6.

Appendix A describes how AWE technologies generate energy.

Appendix B details the assumptions behind the spatial LCOE analysis with additional results.

2. Overview of AWE

2.1. Overview of systems

The devices in development have accumulated hundreds of hours of operation, although few have been run in long-term fully automated cycles. At this stage of maturity, there are three main categories of concepts:

- Ground-generating, reeling tether (tether-gen)
- Onboard-generating (fly-gen), and
- Ground-generating, rotary (rotor-gen).

Although the majority of concepts are ground-mounted, reeling-tether generating, there is also significant variation of those technologies.

Technical achievements

Critical technical challenges have been overcome including:

- Automatic energy harvesting
- Reliable sensors
- Reliable flight state estimation
- Tethered aircraft and kites able to operate in highly demanding aerodynamic load cycles, and
- Automated launching and landing for vertical take-off and landing (VTOL) devices.

Technical challenges

Remaining challenges that are key milestones in the development of AWE devices include:

- Fully automated launching and landing for some concepts (see Table 2)
- Prolonged autonomous operation
- Durable and lightweight materials to sustain a high number of load cycles for soft wings
- Systematically increased reliability, and
- Operational safety assurance, including establishing regulatory requirement.

Most AWE-TDs are developing systems where individual devices operate at 100 kW-scale that can be scaled to several MW. Several companies plan to upscale to 1-3 MW devices over the coming years.

2.1.1 Ground-generating – reeling tether

The most common device type is the intermittent generating solution, also known as 'pumping' or 'yo-yo'.

- The airborne element is tethered to the ground at a fixed location, as shown in Figure 4. Kinetic energy of the air is converted to a force seeking to reel out the tether. The tether is allowed to extend by turning a drum connected to a generator, either directly or via hydraulics or similar.
- Operation consists of two phases:
  - The energy-producing (traction) phase, where the device extends the tether, and so generates electrical energy, and
  - The recovery phase, where a smaller amount of electrical energy is used to pull the airborne element back to lower height.
- The flight path of the device (and hence force on the tether) is controlled, taking advantage of crosswind motion to increase the energy produced in the traction phase and minimise the energy consumed in the recovery phase.
- Devices tend to follow either a helical or a translating figure of eight pattern.
- There may be more than one airborne element per ground-station (or foundation), with shared use of some components, enabling more continuous generation.

Companies developing ground-generating – reeling tether devices include:

- EnerKite
- Kitemill
- Kitenergy
- Kitepower
- Skypull
- SkySails
- TwingTec, and
- Wind Fisher.

Skysails has deployed its first 150 kW single-kite commercial system in Mauritius, and has established a small series production line. [v]

[v] https://skysails-power.com/kite-power-for-mauritius/

Kitepower has deployed a 100 kW device in Aruba as its first full test of logistics and operation outside Europe.[vi]

Further information on reeling tether operation is given in Appendix A.

Figure 4 Ground-generating – reeling tether kite (Source: SkySails)

Figure 5 Containerised ground base station (Source: Kitepower)

2.1.2 Onboard-generating

Fly-gen devices are tethered to the ground at a fixed location. In normal operation, the tether is fixed length.

The power conversion equipment is onboard the device, with one or more rotors driving generators. Power is then transmitted back down to the base station via the tether.

The airborne element flies crosswind to augment the inflow. Motion may be circular or in a figure of eight.

There was also a concept where the generating equipment is supported by a small airship or blimp. Altaeros began work on the Buoyant Airborne Turbine (BAT), however it is currently on hold while the company focusses on other blimp projects.[vii]

Figure 6 Onboard generating device (Source: Kitekraft)

The closure of previously front-running company Makani has not signalled the end of research into fly-gen concepts, as it was developing one specific type. [viii] Kitekraft is an example of an AWE-TD continuing to develop a fly-gen product. It cites three main reasons for why its approach can be successful where Makani was not: [ix]

- Using a boxplane kite increases stability and aerodynamic efficiency
- Focusing on simplicity and low-risk development instead of attempting to achieve maximum theoretical potential, and
- Following a route to market with the smallest possible device as quickly as possible to improve learning for development of MW-scale devices.

[vi] https://thekitepower.com/kitepower-in-aruba/

[vii] Correspondence with Altaeros, June 2022.

[viii] In 2021, the US Department of Energy submitted a report to the US Congress on Challenges and Opportunities for Airborne Wind Energy in the United States. As part of that report, they included an appendix discussing Makani's decision to close and contributing factors. Among others, the report cited lower than expected power performance, premature commitment to a single design architecture, and funding pressure as contributing factors in Makani's decision. https://www.energy.gov/eere/wind/articles/new-report-discusses-opportunities-and-challenges-airborne-wind-energy

[ix] Correspondence with Kitekraft, June 2020.

Similarly, Windlift is an AWE-TD developing another fly-gen product. It cites three main reasons why its approach can be successful:

- Using a patented variable-cross section tether that reduces drag and increases power output
- Employing a deliberate and iterative approach to engineering and incremental approach to scaling, and
- Keeping to a smaller scale with patient capital to explore the design space in depth.

Windlift has completed a US $6.2 million research and development project with the US Marine Corps and US Naval Research Laboratory to design a man-portable airborne wind energy system as a deployable power solution. In mid-2023, Windlift is due to deliver an autonomous, mission-capable 4kW prototype for field testing and evaluation.

2.1.3 Ground-generating – rotary

This is a relatively new generating solution being developed by both Windswept and Interesting and aweSOME Labs called a kite turbine. Windswept and Interesting's work on developing the autonomy of an initial 10kW device is being funded by Shell GameChanger and UK's Highlands and Islands Enterprise, and Shetland Islands Council. The device is fixed to the ground and uses multiple aerofoils, in modular rotors. The rotors connect together with tethers to rotate the structure. By keeping the tethers in tension, the rotation is transmitted to a ground station generator.

Figure 7 Ground-generating rotary device design (Source: Windswept and Interesting)

2.2 Technology development

2.2.1 Current systems

The majority of AWE-TDs are based in Europe, making the progress of leading European AWE-TDs a key measure of the industry's progress. Most systems being developed are ground-generating. A variety of concepts including rigid or soft wing exist.

Table 1 Key Airborne wind device technology developers (AWE-TDs) and system types

Technology developer	System type
Ampyx [x]	Ground-gen, reeling tether, horizontal take-off and landing
EnerKite	Ground-gen, reeling tether, horizontal take-off and landing
Kitekraft	Fly-gen, vertical take-off and landing
Kitemill	Ground-gen, reeling tether, vertical take-off and landing
Kitenergy	Ground-gen, reeling tether, flexible wing
Kitepower	Ground-gen, reeling tether, flexible wing
Oceanergy	Vessel-mounted, reeling tether, flexible wing
Skypull	Ground-gen, reeling tether, vertical take-off and landing
SkySails	Ground-gen, reeling tether, flexible wing
TwingTec	Ground-gen, reeling tether, vertical take-off and landing
Wind Fisher	Ground-gen, reeling tethers, Magnus effect, semi-rigid
Windlift	Fly-gen, vertical take-off and landing
Windswept & Interesting	Ground-gen, rotary

[x] Entered into insolvency in April 2022. A core team is expected to continue under a new company name.

Figure 8 AWE-TD flying devices (Source: suppliers)

2.2.3 Device development

The remainder of the decade will be an important period in determining the competitive potential of AWE technologies as many AWE-TDs seek to mature their concepts into commercially viable systems. A summary of the key milestones that a selection of AWE-TDs have achieved is shown in Table 2.

Most AWE-TDs are developing their first systems that will be taken to market for onshore applications.

Many of this first tranche of systems will form the basis for development of enabling offshore AWE generation, with some suppliers (including SkySails and Oceanergy) having developed concepts suitable to be mounted on vessels.

Table 2 Sample of European AWE-TD milestones achieved

Organisation	Automatic flight	Automatic operation in major phases	Autonomous flights repeated over multiple days	Autonomous operation in all operational phases	Operational hours > 100	Commercial system order agreed
Ampyx®	2012: 15 kW	2015: 15 kW		2015: 15 kW		
EnerKite	2012	2012: 30 kW	2013: 30 kW	2021: 30 kW	2013: 30 kW	
Kitemill	2013: 5 kW	2017: 5 kW 2021: 20 kW		2017: 5 kW	2020	
Kitepower	2016	2018: 100 kW			2019: 100 kW	
Skypull	2019: 1 kW	2020: 1 kW		2020: 1 kW		
SkySails	2008: 1 MW*	2008: 1 MW* 2016: 50 kW	2008: 1 MW* 2020: 200 kW	2016: 50 kW	2020	2021: 150 kW
TwingTec				2018: 2 kW		
Windswept & Interesting					2018: 2 kW	

* denotes vessel mounted system

2.3. Current industry landscape

A healthy innovation ecosystem requires various stakeholders offering different capabilities. This includes AWE-TDs, specific technology developers, research institutes, financiers, government agencies and test facilities. Having a well-resourced innovation ecosystem supports wider learning and opportunities for technologies to be developed sufficiently to have their commercial potential fully assessed.

Need for test and demonstration sites

Test sites need to be established to allow for continuous operation building up operational hours for developing reliable products and industry standards, thus providing evidence to customers and authorities. These require agreement with numerous authorities, including in aerospace, defence and public health and safety. In July 2022, RWE completed construction of an AWE test site in the Republic of Ireland. It will operate for 8 years over which RWE aims to test 3-4 devices, sequentially. This will begin to address the need for test sites, however further similar sites are required, with the sector searching for common test sites in a number of countries including Germany, Spain, and the UK.

Developing policy and regulatory frameworks for AWE

Airborne Wind Europe is the principal industry advocate. In 2019 it published a first roadmap summarising the findings of an Airborne Wind Europe working group.[xi] This roadmap outlined the potential growth trajectories for AWE system deployment, highlighting a belief that GW scale by 2030 and hundreds of GW by 2050 is achievable. [xii]

To achieve these goals, a regulatory framework and industry standards based on IEC 61400 are required to remove barriers to finance and permitting. There is currently no coordinated policy framework for AWE in key markets, in particular in Europe where most of the AWE-TDs are based.

Permitting of AWE devices involves additional regulatory areas including those related to autonomous aircraft. This is a complex environment but the recent European regulation on unmanned aircraft systems (UAS) provides an opportunity to streamline permitting for AWE. [xiii] By way of comparison, permitting is already a key bottleneck in developing established wind technology sites, despite its maturity. For small, innovative AWE-TDs to be able to quickly bring to market and scale up systems to multi-MW scale, a coordinated approach to permitting policy is required.

Airborne Wind Europe members are working on AWE safety and technical guidelines to support alignment of devices facilitating acceptance by aerospace authorities.[xiv]

Access to finance

Private finance from investors has played a central role in supporting AWE-TDs' development programmes, representing the vast majority of funding acquired to date; but that may have come too soon in the development cycle. Finance from governmental bodies, including R&D grants, of about €75 million has been awarded to date, but forms a smaller fraction of AWE-TDs' income. These grants have typically fallen under broader innovation criteria instead of being identifiably AWE-specific funding programmes which makes them difficult to access for AWE-TDs.

The long-term financial viability of AWEs depends upon demonstrating commercial business models and realising routes to market, as demonstrated by established wind technology. Public financial support has an essential role to play to ensure sufficient understanding and performance is demonstrated on smaller systems before scaling up. By de-risking private investment, subsidy has successfully helped bring other renewable generation technologies to maturity.

The recent news of Ampyx Power failing to secure sufficient investment signals the urgent need to secure the support to ascertain the role of AWE in a future net zero energy system to ensure investment can be leveraged.

Consolidation

There is a broad range of devices competing to demonstrate commercial viability. As seen in the development of other technologies, such as established wind, there is likely to be attrition of some concepts as more is determined about device performance and LCOE. It is not expected that there will be a dominant design as occurred for the three-bladed horizontal axis wind turbine especially given the different markets and applications for AWE.

Some AWE-TD product programmes have closed, most notably Makani in 2020 with the intellectual property published. [xv]

Social Acceptance

Public acceptance has impacted the deployment of other renewable energy technologies in the past, notably with established wind technology.

Existing literature suggests AWE has higher social acceptance than existing wind technology, but empirical evidence for this assessment is still lacking. A joint study is underway by members of Delft University of Technology and the Amsterdam University of Applied Sciences to assess the social acceptance of AWE.[xvi]

This study will help achieve a more accurate understanding of how different stakeholders, including hosting communities, perceive and respond to the technology. For the long-term success of the industry, it is important to identify critical acceptability issues at an early stage of technology development and to engage relevant stakeholders in the development and deployment of AWE.

[xi] https://airbornewindeurope.org/about-airborne-wind-europe/working-groups/working-group-aweurope-roadmap/

[xii] https://airbornewindeurope.org/wp-content/uploads/2020/09/AWEurope_WG-Roadmap_2019.pdf

[xiii] Implementing Regulation 2019-947 and Commission Delegated Regulation (EU) 2019/945 on unmanned aircraft systems (UAS)

[xiv] https://airbornewindeurope.org/working-group-awe-safety-and-technical-guidelines/

[xv] https://blog.x.company/a-long-and-windy-road-f8e09d02c9e1

[xvi] Schmidt, H. S., de Vries, G., Renes, R. J., & Schmehl, R. (2022). Social Acceptance of Airborne Wind Energy. In R. Schmehl, L. Fagiano, A. Croce, & S. Thoms (Eds.), 9th international Airborne Wind Energy Conference (AWEC 2021): Book of Abstracts (pp. 34)

3. Benefits of AWE

AWE is wind 2.0 – a game-changing solution accessing the large untapped wind resource potential at heights above those accessed by established wind technology. It enables more energy to be extracted at lower carbon intensity and eventually at lower cost. [xvii]

We suggest that Europe and other areas in the world need to access all viable natural resources they can, and AWE, alongside established wind technology, should be considered as one of the key solutions to our energy challenge. The markets for established wind technology, solar PV or other renewable technologies will continue to grow significantly.

AWE offers a complementary solution to increase the overall deployment of renewable technologies. There may also be hybrid sites where AWE is combined with other renewables, including established wind increasing the energy yield of a site.

AWE is worth developing, for the following reasons:

- AWE opens up new areas for energy production from wind
- AWE can (in time) deliver much more energy per square kilometre than established wind technology
- AWE can (in time) provide energy at lower cost than established wind technology, and
- AWE has lower environmental impact.

3.1. AWE opens up new areas for energy production from wind

Primary benefits

Europe and other areas in the world should benefit from all viable natural resources in their rapid move to net-zero electricity production and increasing their energy security of supply.

- Delivering all wind demand needed from established wind turbines alone will be challenging. The wind market needs AWE.

- AWE enables access to a larger wind resource potential at heights above established wind turbines. Figure 9 shows optimal wind speeds at up to 500 m height compared to at 100 m fixed altitude. Increases in wind speed have a significant impact on the energy production and cost of energy.

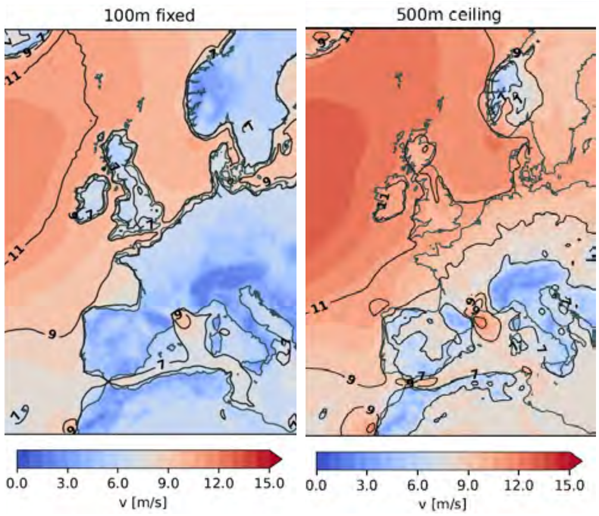


Figure 9 Average wind speed at 100m fixed and 500m ceiling above ground level. [xviii]

Europe currently has 207 GW onshore wind capacity, and the European Commission has a vision for this to increase to 1,000 GW by 2050 as part of its net-zero vision.[xx] This means that many more wind sites need to be developed.

Many countries are already struggling to find enough viable sites for onshore wind (hence the move in focus to offshore wind). The UK, for example, has committed to 50 GW of offshore wind by the end of 2030. This is significantly higher than its 2030 onshore wind target of 30 GW despite having an excellent onshore wind resource, because it recognises that it is running out of onshore sites.

AWE has a much lower logistics requirement than established wind technology, hence it can be installed in places that established wind cannot. Many of these are high-wind areas offering low LCOE.

- For example, a standard-scale onshore established wind turbine has maximum transport breakpoints of 4.6 m width, 63 m length and 36 t mass. For many sites, road bridges, gradients and corners limit the viable size of turbines that can be installed.[xxi]

Secondary benefits

Eventual lower LCOE from AWE also means more areas are viable for energy generation from wind.

AWE's lower mass, easier installation and transportation, and potentially lower forces on a foundation are expected to make it an option for offshore wind, especially floating.

xvii Established wind turbines are horizontal axis wind turbines which are used onshore and offshore.

xviii Bechtle et. Al., wind data: ERA5.

xvx https://windeurope.org/intelligence-platform/product/wind-energy-in-europe-2021-statistics-and-the-outlook-for-2022-2026/

xx https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5de5dd27f&appId=PPGMS

xxi https://www.nrel.gov/docs/fy16osti/67014.pdf

3.2. AWE can deliver much more energy per square kilometre than established wind technology

Primary benefits

With Europe and other areas in the world needing more energy production from wind, AWE can play an important role by using available space up to about three times more effectively.

- Established wind turbines are highly efficient at extracting energy from a concentrated area, which means they need to be spaced out to avoid wake effects.
- AWE devices extract energy over a much more spread-out area, so form much smaller wakes and are able to be controlled to avoid wakes of other devices.
- AWE accesses a larger wind resource potential at heights above established wind turbines.

This means AWE can deliver more energy on any given site. Proof of the precise improvement factor will come following practical experience operating multiple AWE projects, but it is likely to be significant. This either reduces the need to use so many lower-wind (so higher LCOE) sites, or enables the generation of more renewable energy.

If Europe used half AWE, half established wind technology, then it could get up to twice the energy production.

AWE has a higher capacity (load) factor than established wind technology on the same site, with figures over 60% anticipated on sites with good wind resources. This means that (as for offshore wind), AWE is closer to acting as 'baseload' than established onshore wind technology or solar.

Secondary benefits

AWE is able to be used in hybrid systems with diesel (in the short term) and other renewables to suit existing sites and grid connections.

Retrofitting AWE especially to PV parks could exploit the differences in energy generation at different times, giving firmer power and a boost to capacity factor. Retrofitting to established wind farms has also been proposed.

Flexibility from being containerised can enable temporary deployment. The H2GO VOF Dogterom project is seeking to use an AWE device and mobile solar panels to generate sustainable energy and produce green hydrogen on fallow land as part of crop rotation. [xxii]

The portability can also enable deployment at sites where there is uncertainty about how long a site may be available and where established wind turbines would not be used due to high cost of moving them later.

3.3. AWE can provide energy at lower cost than established wind technology

Primary benefits

Although currently higher cost, with public investment in technology development, by the early 2030s AWE will be able to compete with an average price lower than established wind technology in the mid-2030s, as discussed in Section 4.3.

Secondary benefits

By harvesting the larger wind resource potential at heights of 300 to 500m, AWE will be viable on more sites that are not viable for established wind technology.

AWE offers more opportunity for efficiency improvement when making planned component changes and thus LCOE improvement during the operating life of projects:

- In established wind turbines, new condition monitoring or control systems can be introduced, but it is not usually viable to replace major components (like blades) to substantially increase energy production.
- In AWE, there are more opportunities due to more planned replacement of components such as kites during the life, enabling replacement with components to enhance performance, providing the opportunity for reducing the LCOE of operating projects.
- Serial production of AWE requires smaller facilities than wind turbines. There is the potential to apply similar process improvements as used for volume production of trucks, giving AWE the potential to benefit from faster cost reduction than established wind technology.

[xxii] https://opwegmetwaterstof.nl/verduurzaming-landbouwbedrijven-met-waterstof/

AWE can also be seen as a hedge against commodity price and cost of money increases, improving the competitiveness over established wind technology. As far less material is used, AWE will become more competitive should commodity prices increase significantly, in a future resource-constrained world.

- As AWE has only 15% of total lifetime project spend up-front (compared to 40% for established wind technology, comparing representative systems for installation in 2025), AWE again will become relatively much more competitive should the cost of money increase significantly, as many economies exit a historically low-inflation period.

AWE offers a potentially more attractive investment opportunity, again due to lower CAPEX investment, than for established wind turbine projects.

3.4. AWE has lower environmental impact

Primary benefits

Established wind technology (at about 10 kg/MWh) has much lower carbon intensity than fossil fuels (at 500 kg/MWh), but as we look to net zero, even this intensity will be a challenge to offset.

AWE has 40% lower carbon intensity than established wind technology, fundamentally because it uses much less material.[xxiii] Some concepts may have as much as 90% lower carbon intensity.

The established wind industry is already the largest user of carbon fibre and cast iron, globally. By 2050, it is estimated that the established wind power sector in Europe alone will have created 190,000 t of carbon fibre reinforced plastic waste. [xxiv]

To deliver 200 GW of AWE by 2050 will use much less material than established wind turbines use.

Impact on birds and bats is likely to be less than established wind turbines.[xxv]

The relative ease of installation for onshore and offshore AWE means decommissioning also has less local environmental impact than established wind turbines.

Secondary benefits

The potential for serial production in a range of facilities can provide greater efficiency.

Relocation and redeployment may benefit sites where demand is seasonal.

Evidence suggests social acceptance may be less of a barrier than has been and is the case for established wind technologies.[17]

[xxiii] https://airbornewindeurope.org/megaawe_airbone-wind-energy-system-life-cycle-analysis_2021-09-29-2/

[xxiv] https://www.researchgate.net/publication/328738188_Anticipating_in-use_stocks_of_carbon_fibre_reinforced_polymers_and_related_waste_generated_by_the_wind_power_sector_until_2050

[xxv] https://airbornewindeurope.org/about-airborne-wind-europe/working-groups/working-group-environment-and-public-acceptance/

4. Route to volume market impact

We modelled a growth scenario for AWE to determine a representative LCOE trajectory, allowing cost comparison with established wind and other generation technologies. Some projects will have a higher and some will have a lower LCOE than the representative LCOE.

Based on the current status of AWE development, we mapped out a realistic sales profile to 2026, as shown in Table 3.

For the longer-term period to 2050, we blended the early growth scenario with the historic development of established wind technology, offset by 40 years.

4.1. Early growth (to 2026)

The initial AWE market is likely to grow where established wind turbine technology is not viable, especially due to logistics. To get to significant volume AWE needs to compete with established wind turbines on a wide range of sites.

AWE is expected to benefit from the understanding and processes developed for established wind technology, as well as aerospace/drones. For example, the industry is engaging with the processes of wind turbine type certification and aviation safety compliance to enable bankable projects.

As with established wind, the needs for permitting at volume are expected to be addressed in parallel with the industry growing.

The rate of early growth will depend on the bankability of the technology (including the role of certification), permitting (especially establishing regulatory frameworks) and the time it takes to develop an onshore site (including securing revenue support). There is much that can be learnt from established wind to accelerate this.

The rate of growth will also depend on how well the industry builds a healthy pipeline of sites. This is a current focus for the industry.

The first commercial 150 kW AWE single-kite system was supplied by SkySails in 2021.

We assumed the sales profile in Table 3 for the leading AWE device supplier.

Table 3 Example of realistic sales profile in the years 2021 to 2026 for the first mover.

Year	Sales (kW)	Description of sales
2021	150	First 150 kW AWE single kite system
2022	450	450 kW system
2023	750	First array of 5 x 150 kW devices
2024	4,000	4 arrays of 5 x 200 kW devices
2025	16,000	8 arrays of 10 x 200 kW devices
2026	32,000	16 arrays of 10 x 200 kW devices

At least four other companies are following with 50-150 kW devices and are expected to achieve installations in the period 2022 to 2025. Together the expected total cumulative market reaches over 90 MW by the end of 2026.

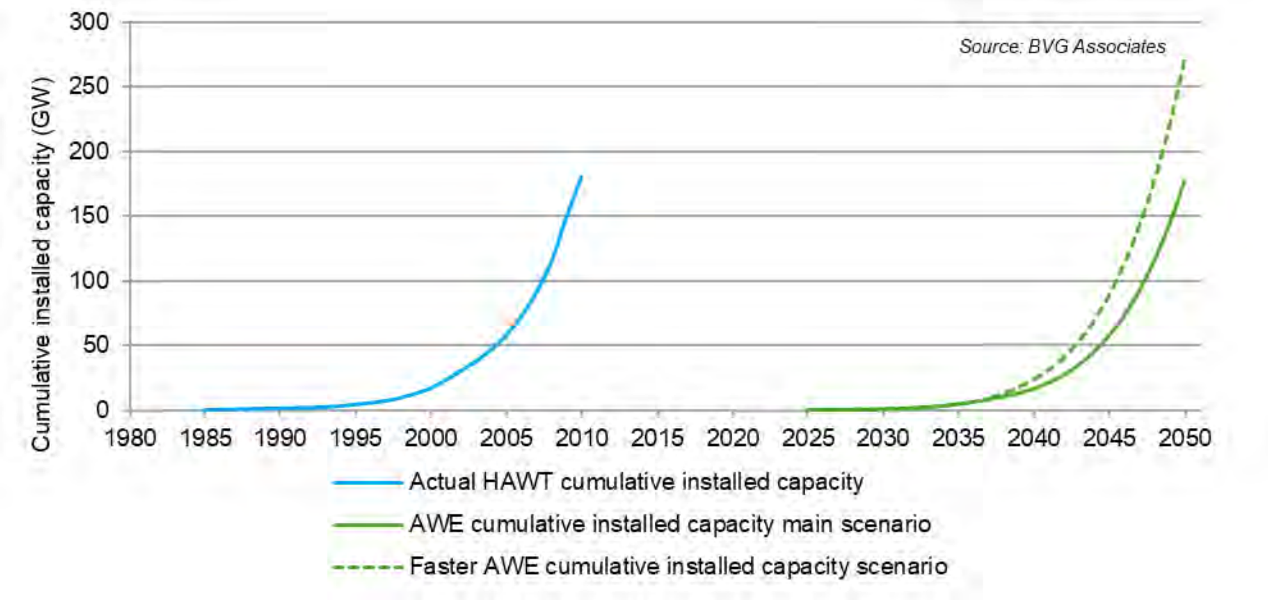


Figure 10 Global cumulative AWE installed capacity scenario with the established wind turbine market it mirrors from 1985 to 2010.

4.2. Longer term growth (2026 to 2050)

Our scenarios for market growth are presented in Figure 10 and Figure 11. The main scenario is based on assuming that the AWE market follows the same trend as the established wind turbine market, 40 years later. The established wind turbine market from 1985 to 2010 is shown and then assumed for AWE from 2025 to 2050. Though somewhat arbitrary, we have done this because the established wind turbine market is a real example of a pattern for growth. The cumulative worldwide installed AWE capacity by the end of 2050 is 177 GW. At a country level, the cumulative installed AWE capacity at the end of 2050 is expected to be 27 GW in Germany and 5 GW in the UK. The UK capacity looks relatively small compared to that of Germany, because the UK uptake of established wind technology began later and has half the installed capacity.

AWE technology is expected to benefit from many markets already having renewable energy frameworks in place, a strong global pull for low-carbon solutions, and a finance community that understands variable generation renewable technologies. This means that it has the potential for faster growth illustrated by the dashed curve in Figure 10 that has a cumulative installed capacity by the end of 2050 of 271 GW.

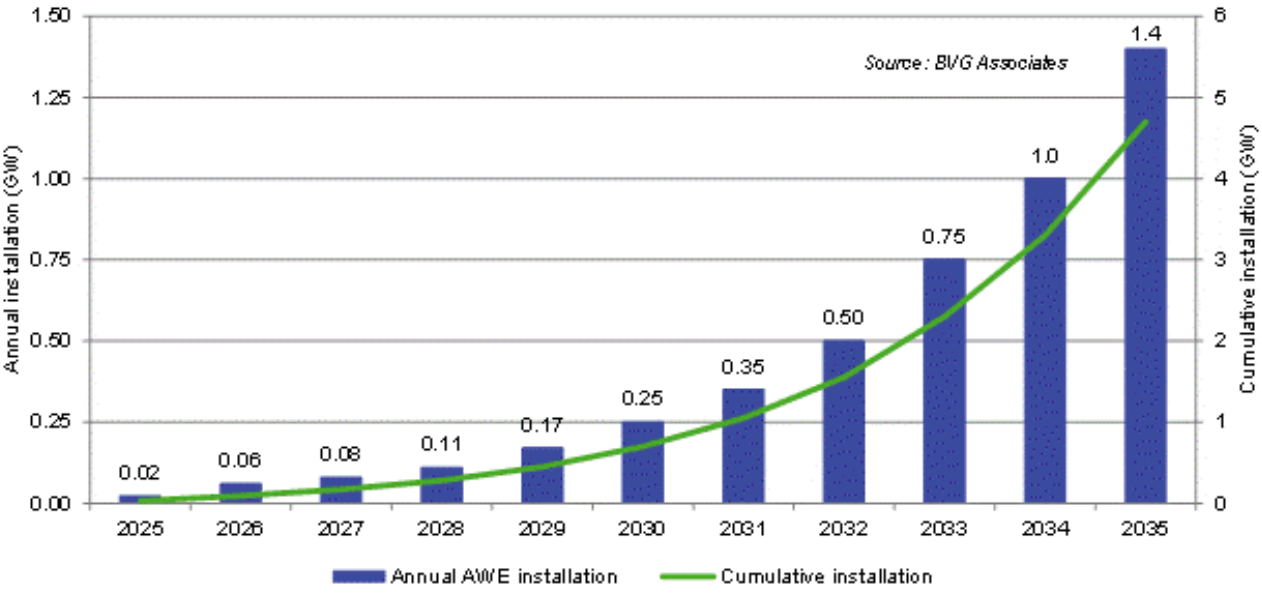


Figure 11 Global AWE initial installation from 2025 to end 2035.

4.3. Cost of energy

We established an LCOE model using inputs confirmed with Airborne Wind Europe members to be a representative system for 2025. This assumed a typical 'central case' site with annual mean wind speed of 7.5 m/s at 100m height. This modelling exercise did not seek to quantify or compare different AWE concepts.

We developed a baseline, representative AWE LCOE by adapting prior work BVGA had conducted analysing AWE LCOE.

We calculated the LCOE trend for AWE out to 2050 based on learning rates applied to the market volume scenario, building on our understanding of AWE cost reduction opportunities and the similar journey that established wind technology has been on for the last 40 years.

We modelled future LCOE trajectories to 2050 for AWE and established wind technology on a like-for-like basis, as shown in Figure 13, from cost and energy production forecasts and using learning rates for established wind of 10% and for AWE of 15% to 2030 and 10% thereafter.

We can have confidence in an eventual 40% lower LCOE for AWE compared to established wind technology because:

- The material cost for AWE already is 70% lower than for established wind technology, for a project producing the same amount of energy.
- Much of the future development is in technologies relevant to drones, unmanned aircraft systems and low carbon aerial transport, with many synergies with tomorrow's industries.
- Installation of AWE devices is easier and quicker than established wind turbines. While finding sites may be more a more complex task given height and permitting requirements, the ease of AWE installation should mitigate any challenge.

A ground-generating reeling tether single wing system was used as the basis for the cost model. Project parameters are shown in Table 4 for 2025, 2030, 2040 and 2050. Resulting LCOEs are presented in Table 5.

[xxvi] BVG Associates for KPS, Cost of energy and market assessment Phase 2 spatial analysis to support commercialisation strategy, 2018, https://kitemillweb-storage.blob.core.windows.net/publicdata/BVGA-22503-Report-r2.pdf

In comparison with established wind technology, the up-front costs for AWE systems are significantly lower, with CAPEX representing 15% of total discounted project costs versus about 40% for established wind projects.

Figure 12 shows the split of development expenditure (DEVEX), CAPEX, operational expenditure (OPEX), and decommissioning expenditure (DECEX) for established wind and AWE. Operating costs for AWE projects represent a greater share of total project costs due to planned component replacement.

The project size and rated power in Table 4 are indicative estimates.

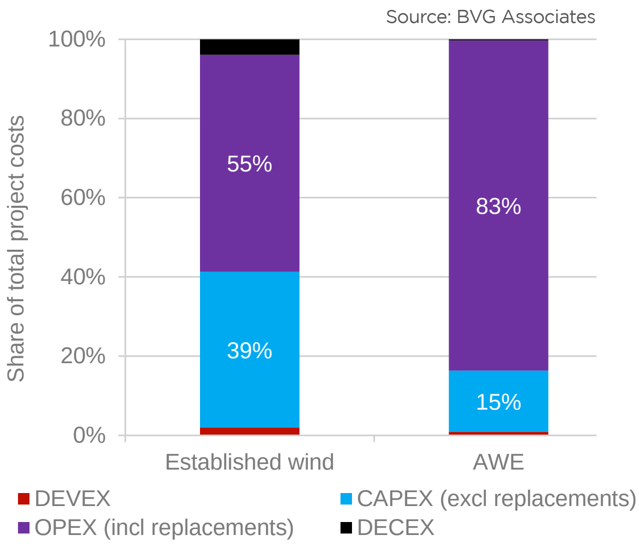
Table 4 Modelled AWE project parameters, 2025 to 2050

Installation year	2025	2030	2040	2050
Wind speed at 100m (m/s)	7.5	7.5	7.5	7.5
Wind shear exponent	0.1	0.1	0.1	0.1
Lifetime (years)	20	20	20	20
Standard WACC	7.5%	5.0%	4.7%	4.5%
CAPEX contingency	20%	15%	10%	5%
Decommissioning % of installation	50%	50%	50%	50%
Market scale (GW)	0.03	0.7	17	177

Table 5 AWE representative LCOE, 2025 to 2050

Installation year	2025	2030	2040	2050
LCOE (€/MWh)	99	45	24	15

Figure 12 Indicative share of total project costs for representative AWE and established wind technology installed in 2025.



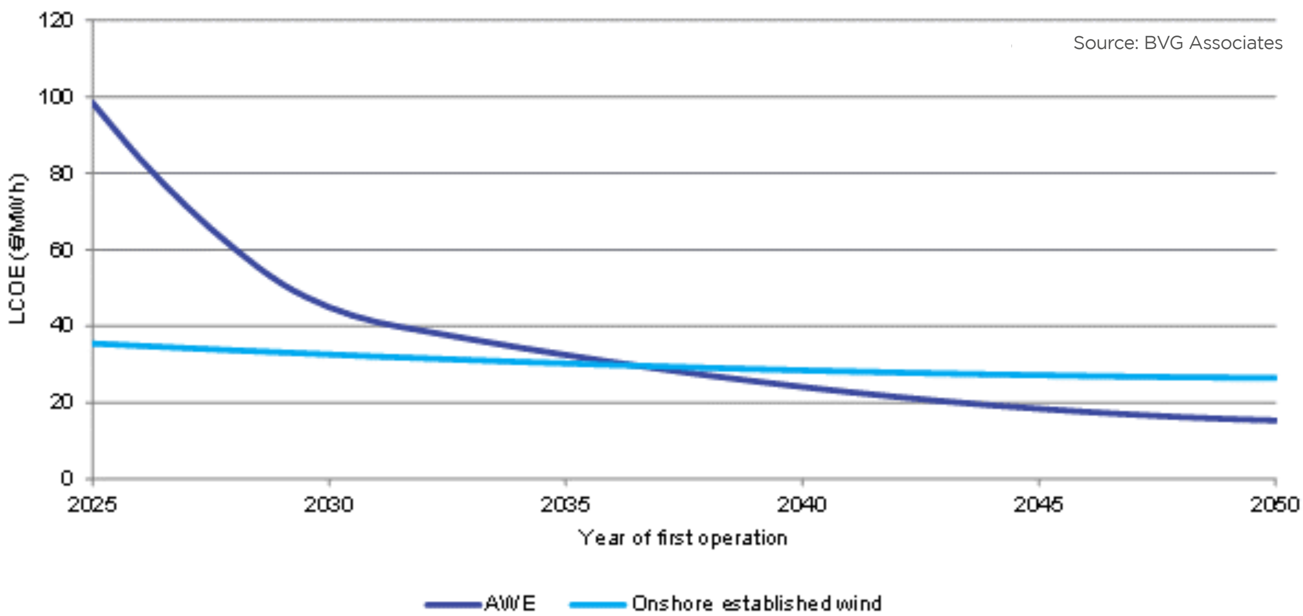


Figure 13 Trend in representative LCOE of AWE and established wind turbine technology

5. Spatial analysis 500 kW onshore projects

In this section we consider how the costs of similar, relatively small-scale systems of different technologies compare with time and location. By fixing the project size to 500 kW, this analysis does not seek to compare costs of state-of-the-art scale technology, as in Section 4.

5.1. Technology baselines

To illustrate areas in the world where AWE is likely to be most competitive, an onshore spatial analysis was conducted to explore how AWE competes with other generation technologies (established wind, solar PV and diesel generators) in the years 2030 to 2050. The results of this analysis, along with underlying assumptions are shown in Appendix B. To enable a like-for-like comparison, a project size of 500kW was assumed.

This analysis divided all onshore locations globally into 10km-by-10km squares. For each location and technology, energy production was modelled using the assumptions in Appendix B. This energy production was combined with capital and operational costs for each technology type in 2030, 2040, and 2050 to calculate LCOE for each technology in each year.

5.2. Technology comparision

We used the technology baseline spatial analysis to compare the cost of the AWE systems and the cheapest alternative generation technology in 2030, 2040, and 2050, considering solar PV, established wind technology and diesel. Diesel generation was consistently significantly more expensive, with the exception of a small number of oil-producing countries in North Africa and the Middle East that have exceptionally low fuel prices. Despite this, solar generation was the cheapest technology in these countries.

The results of these comparative analyses are shown in Figure 14 to Figure 16.

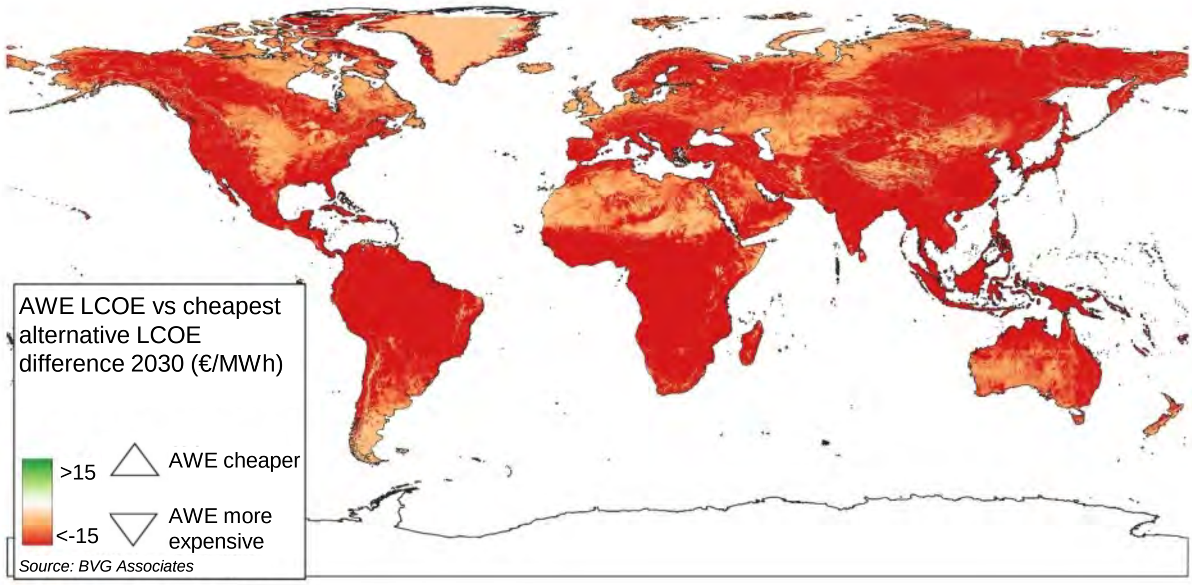


Figure 14 Global LCOE for representative AWE system versus cheapest alternative in 2030 for 500kW project.

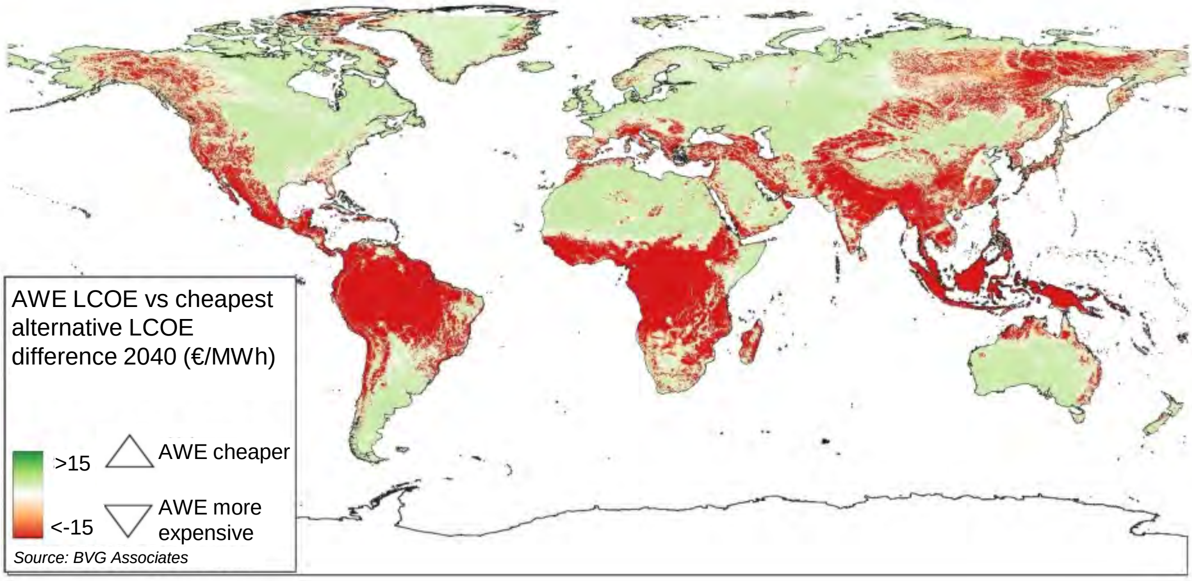


Figure 15 Global LCOE for representative AWE system versus cheapest alternative in 2040 for 500kW project.

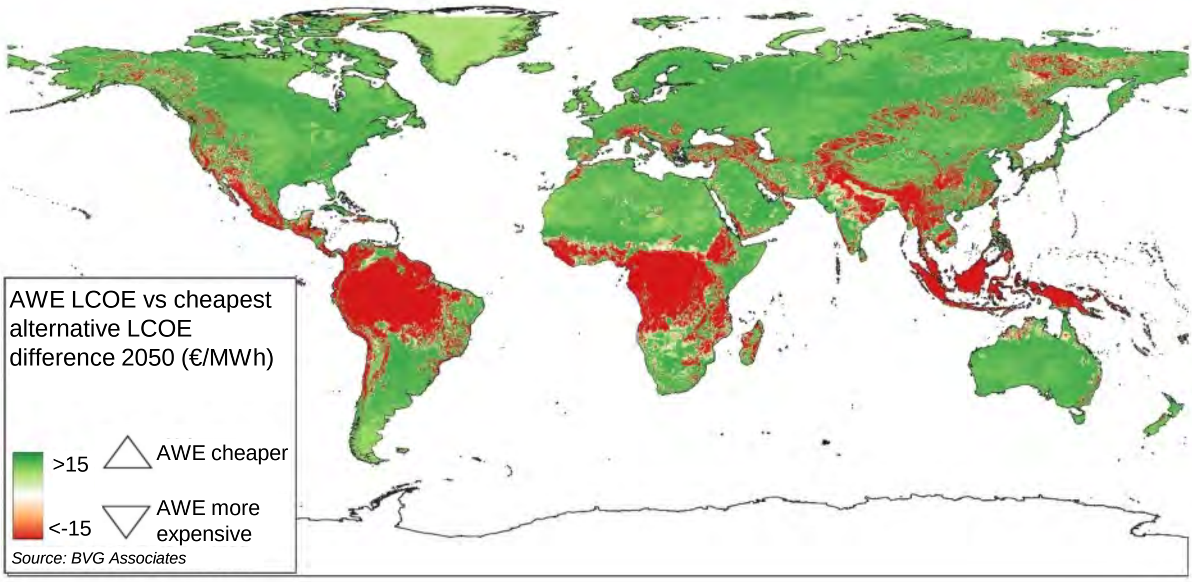


Figure 16 Global LCOE for representative AWE system versus cheapest alternative in 2050 for 500kW project.

5.3. Global competitiveness

The results of the spatial analysis shown in Figure 14 for 2030, shows that AWE is cheapest in a small number of areas in Greenland and Chile and marginally competitive (light red) in some areas of North Africa, Asia, South America and Australia.

By 2040, the cost comparison picture shown in Figure 15 is significantly changed. AWE is the cheapest source of generation for more than half of the onshore surface, including large parts of North Africa, Asia, South America, and Australia.

The results for 2050 in Figure 16 show this trend continuing, with AWE moving from being marginally competitive (light green and white areas in Figure 15) to being a far cheaper form of generation (green areas), and the cheapest form of generation in over 60% of the onshore surface.

5.4. Key markets and adoption

The analysis shows that northern Europe and central North America can be key markets for deployment of AWE at a large scale by 2040. This shows the need for AWE to demonstrate viability at grid-scale within a decade.

Early adopters of AWE are an important part of achieving this market penetration, where customers experience higher prices of electricity or have limited other sources of electricity. To be adopted quickly enough to start making an impact on climate change, however, adoption needs to happen at grid-scale early on.

Potential market segments for early adoption are shown in Table 6. Enabling activity in many market segments is key to achieving the market volume needed to rapidly reduce LCOE and so ensure markets become self-sustaining.

The transition from smaller-scale to grid-scale applications is crucial for AWE to tap the market potential shown in this analysis. While progress is being made, such as SkySails deployment of a 150 kW device in Mauritius, there is an urgency to overcome the barriers to large-scale deployment in key global markets.[xxvii]

xxvii https://skysails-power.com/kite-power-for-mauritius/

Table 6 Summary of specific markets where AWE has technical advantages

Market segment	Benefits of AWE	Challenges for AWE
Grid connected	Enables wind power to be harnessed at sites especially those not otherwise suitable for established wind technology or where other renewables already installed. Price support for such sites is most likely to drive economies of scale and so achieve LCOE reduction quickly.	Permitting frameworks for up to 500 m above ground operation are not in place. Availability of sites with enough wind resource at established wind hub heights so sites are used for established wind not AWE.
Low wind sites	Accessing winds at higher altitudes than established wind means lower wind sites can become viable.	Permitting frameworks for up to 500 m above ground operation are not in place. Availability of alternative sites with good wind resource at established wind hub height
Difficult to access terrain including islands	Light installation footprint enables deployment where established wind technology cannot be installed.	Lower demand in difficult to access terrain reduces potential for large-scale grid-connected deployment. Difficult logistics; potentially only one-off-projects.
Hurricane and typhoon regions	Easy demobilisation of flying elements can ensure systems are protected.	No challenge specific to AWE.
Auxiliary supply on vessels	Low loading forces from the device make connecting systems on existing vessel decks possible.	Significant requirement for testing at sea.
Reuse of offshore platforms	Low loading forces offers potential for repowering existing established wind offshore foundations and extending useful life. Especially relevant for the small early offshore wind farms whose case for repowering with established wind technology is poorer.	Probably needs AWEs rated over 2MW. Not proven.
Offshore floating	Low loading forces from the device offers potential for smaller floating foundations.	Probably needs AWEs rated over 2MW.
Hybridisation of remote diesel generators	Offer renewable alternative to running diesel generators fulfilling existing demand. Wind diesel systems are a mature technology.	No challenge specific to AWE.

6. Offshore AWE potential

AWE devices have been operated from vessels providing an auxiliary power source and this market is expected to develop using the devices described for onshore wind.

Once larger MW-scale AWE devices are available, these are expected to be applied similarly to established offshore wind. They could be attached to offshore platforms and operate in a similar way to their onshore counterparts. This is expected to happen for single AWE devices of 2 MW or possibly 3 MW. This is a significantly smaller rating to established wind turbines that are currently being installed at 10 MW and the 14 MW expected to be installed in 2023. It is likely that more than one AWE device may be installed on a single foundation.

Where water depths and seabed conditions allow, fixed foundations can be used, whereas in deeper water, floating solutions will dominate.

6.1. Potential benefits of AWE for offshore applications

- As AWE devices can operate in regions with lower sea-level wind speeds, the potential area for development is larger than for established wind technology.
- The ports and vessels requirements are easier for airborne wind, as the foundation itself is smaller and there is no tower to handle; therefore, there is no need for working with equipment at-height in the same way as for tower-based established wind turbines. This means that unlike for established turbines, specialised port infrastructure and installation vessels are not needed.
- The reduced lateral loads in comparison to established wind technologies mean AWE devices produce far lower turning moments on base structures. This enables cheaper construction, application on vessel decks, or use of existing structures for lifetimes extended beyond their rated duration for established wind technologies. This feature is perceived as having the most benefit for floating foundations, giving savings in foundation size compared to a comparably rated floating established wind. Since foundations will be smaller, savings may also arise from more suitable facilities being available without the need for significant investment.
- The greater power density of wind farms with AWE devices is expected to enable more energy generation for a given area of seabed. For countries with more limited areas of sea, the amount of energy generated may give a greater benefit in the future than a price per MWh.
- When existing offshore wind farm foundations come to the end of their life for use with established wind turbines, installing AWE devices may prove to be a cost-effective option of reusing the foundations and transmission infrastructure.

6.2. Constraints of AWE for offshore applications

- The safety requirements around AWEs may be more constraining for airborne wind sites, because of the risk of the airborne device failing in such a way that it affects a larger area of seabed. If mitigation of this risk requires that only authorised vessels enter the area of the farm, this could reduce the possible regions of operation.
- The take-off-and-land areas needed on the base structures are large in comparison to the working areas on established wind technology base structures. These need to be located higher than that of an established wind floater and tower interface above MSL to avoid wave breaking (so will require a relatively short tower and platform).

6.3. Indicative LCOE comparison

BVGA has modelled LCOE for wind farms with floating AWE, and floating and fixed bottom established wind technology turbines. Established floating wind is on its own journey of cost reduction, and that installed in the mid-2030s is expected to benefit from the learning from being deployed in large wind farms. By the mid-2030s, its average LCOE is expected to have more closely approached that of the average established bottom-fixed wind but will possibly never reach it. Nonetheless, it is expected to be installed at volume as it opens new locations that established bottom-fixed that established bottom-fixed wind cannot serve. In contrast, deploying AWE offshore will not open a comparable new market, so to be deployed at scale it will ultimately need to compete on price with floating offshore wind using established wind technology.

Larger AWE devices may offer benefits that allow AWE entry into the offshore wind market. Though there are savings in foundation size versus that of a comparably rated floating established wind, these do not translate into large savings in materials and therefore cost. The smaller AWE devices and foundations may, like for onshore, offer advantages in lower cost production but these might not offer reductions in LCOE beyond those expected to be achieved by increases in established wind turbine size.

It will, therefore, be the underlying cost reductions of the AWE technology deployed initially onshore or on vessels that will be key to the route to expand an AWE offshore wind market.

If the potential benefits are realised, AWE floating has the potential to be delivering a LCOE not that far above the other wind technologies in the mid-2030s.

AWE floating will need to deliver prices at or below floating established wind to achieve a significant market.

The AWE-TDs should remain focussed on design of the AWE devices themselves rather than future floating foundations. When the time comes, the offshore wind approach will be to choose the best floating support structure available at the time, rather than optimising any AWE design around a bespoke structure.

7. The AWE sector ask

€5 billion of public support is needed to enable AWE to deliver these benefits, with net benefit already in 15 years.

7.1. Potential benefits of AWE for offshore applications

With support, the cost of AWE will break even with established wind technology in about 2036 as shown in Figure 13.

- From 2033 it will need a gradually decreasing amount of public support
- After this, lower LCOE than established wind technology means AWE will provide huge payback to consumers, with break-even already in 2040, and
- There will continue to be a market for both AWE and established wind technology, as different sites are suited to each. The net generation cost benefit by 2050 is over €100 billion. This excludes accounting for environmental and security of supply benefits.

The extra price support to get AWE to this break-even compared with the cost of established wind technology is about €4 billion as shown in Figure 17, when just over 10 GW of AWE will have been installed. Most of this will need to come from public support. For context, this is the price of a single 1.2 GW offshore wind farm.

A faster growth rate of installed AWE capacity beyond 2035 is also possible as shown in Figure 11. Although, this potential upside makes little impact on the need for the €4 billion of public support in the years before 2035, the net generation cost benefit by 2050 would be considerably higher.

We suggest price support possibly as a FiT initially in 2023 of 200 €/MWh and dropping with time in line with LCOE reduction. The provision of such support systems across Europe will enable certainty of access to revenue, as well as ensuring the focus of technology development is tied to energy production.

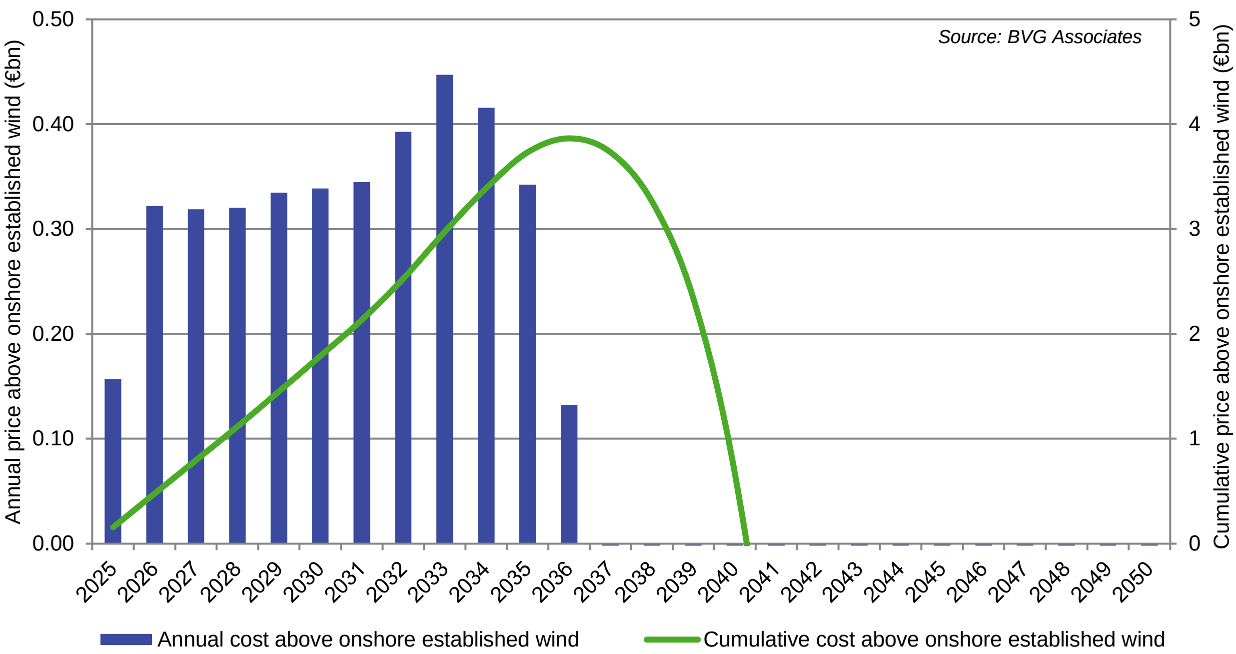


Figure 17 AWE price in excess of that for established wind turbines showing that premium lasts until 2036.

7.2. €125 million per year industry development support needed

Other public support is required, growing to about €125 million a year between 2023 and 2030 with additional funding from the industry and investors. Table 7 shows how that spend is expected to break down. Ideally this would form part of an AWE Development Programme joint initiative of various governments to support the AWE journey to commercialisation, but it is as important that seeking such joint activity does not delay any country or group of countries taking action. Table 8 shows a scenario of how the funding needed could be spread across countries. So far about €75 million of public funding has been awarded to AWE to date. Some of that is included in the spend identified below for future years.

Table 7 Type of public support in AWE development

Area of support	Note	Fraction of other public support
Direct innovation grants	Includes funding prototype testing	60%
Supply chain development grants	For equipment and expertise to assist manufacturing	10%
AWE test site grants or sponsorship of electricity produced	For provision of open access test sites and their operation and developing associated performance verification. At least 5 grid connected sites that allow 24/7 unrestricted operations are needed.	5%
Site development grants	Grants for those seeking to develop the first AWE farms	5%
Acceleration support	Tailored business growth support for each grant recipient. In addition to the direct grant itself mentioned above, providing acceleration support is also necessary to ensure grants achieve their intended outcome. An example where acceleration support has been demonstrated as successful is the UK Energy Entrepreneurs Fund	5%
Grant programme support	For programme development, competitions and their launch, grant monitoring: administering grants above	5%
Support for standardisation	Develop guidance and standards needed	5%
Addressing regulatory barriers such as permitting especially related to air traffic	Resource for regulators and planning bodies to develop and administer the frameworks needed for AWE to be deployed at scale.	5%

Table 8 Scenario of spread of AWE public funding support (€million)

Funding for	2023	2024	2025	2026	2027	2028	2029	2030	**Total**
EU	8	15	30	40	50	50	25	13	**230**
Large European States (DE, ES, FR, IT, UK)	18	35	70	90	100	100	50	25	**488**
Other European States	10	20	40	40	40	40	20	10	**220**
US	4	8	15	25	25	25	13	6	**120**
Total	**39**	**78**	**155**	**195**	**215**	**215**	**108**	**54**	**1058**

7.3. Key milestones

Key milestones to benchmark public support for successful development of AWE are:

- The number of devices exceeding autonomous generation over 100 hours
- Number of devices installed including pilot projects
- Size of project pipeline
- Generation and other performance measures of projects where reporting this could be require as part of price support, and
- Size of multi-device array projects coming online.

The need to spend much of the public money identified above will only arise after progress has been demonstrated against the early milestones.

7.4. Summary

Public support of about €5 billion is needed, split as €4 billion for project electricity price support and €1 billion for industry development support.

As with all new energy technology:

- This ensures sufficient R&D happens,
- Companies have the necessary stability to efficiently undertake the technology and product development,
- Regulatory regimes are established,
- The first commercial projects go ahead,
- The environment needed for AWE technology to be deployed at volume in existing markets is established, and
- AWE is able to properly develop to compete with established wind technology.

Given AWE is such a promising technology, with such potential to help in the fight against climate change, provision of support to accelerate its development is urgently needed.

Appendix A Energy generation

Ground-generating – reeling tether

Flight

Most systems use the fixed-location ground-generating reeling tether concepts described in section 2.1. Figure 18 illustrates the helical or translating figure of eight flight pattern during the 'traction' phase that turns a ground-based generator by the force applied through the tether. The flying device then transitions to a 'reel in' phase where the wing is de-powered via an automated avionics system to minimise the energy used as the tether is wound in ready for the next generation cycle. Figures courtesy of Roland Schmehl. [xxviii]

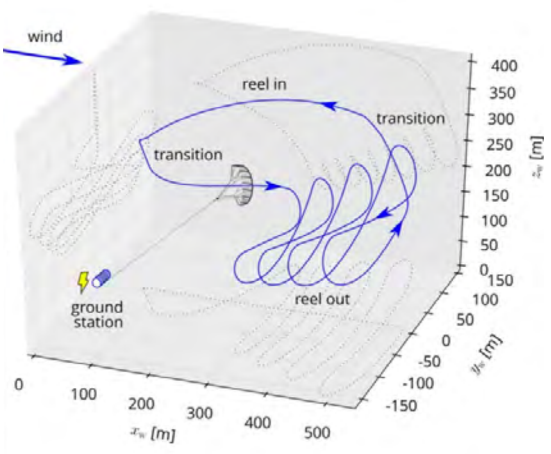


Figure 18 Representation of flight stages for ground-generating reeling tether fixed systems.
(Source: Roland Schmehl)

When sufficient wind is available devices follow their generation cycle flight paths. If wind speeds fall below those required for flights devices will be automatically reeled in until wind speeds return sufficiently for automated flight cycles to be initiated.

Devices will be temporarily removed from service for operational reasons such as planned or unplanned maintenance and component replacement.

Energy output

The 'pumping' or 'yo-yo' generation patterns result in phases of generation and energy consumption shown in Figure 19. The average cycle power is calculated based on the energy generated over complete cycles. The rated power of a device is the maximum average cycle power which will be generated at the optimum wind speed as shown in Figure 20.

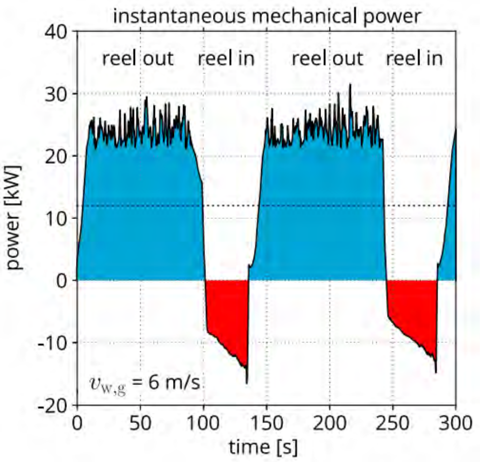


Figure 19 Representation of power generation for a single ground-generating reeling tether device.
(Source: Roland Schmehl)

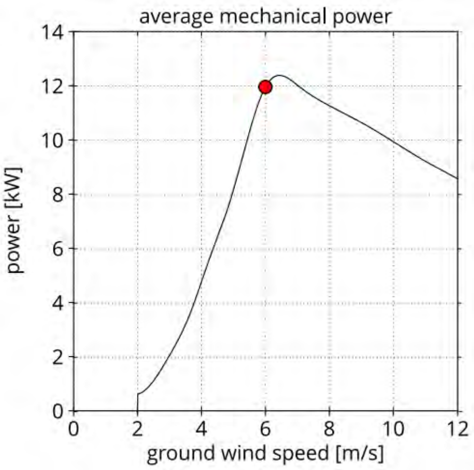


Figure 20 Power curve for a single ground-generating reeling tether device rated at 12.3 kW.
(Source: Roland Schmehl)

[xxviii] Zillmann, U., Bechtle, P. (2018). Emergence and Economic Dimension of Airborne Wind Energy. In: Schmehl, R. (eds) Airborne Wind Energy. Green Energy and Technology. Springer, Singapore. https://doi.org/10.1007/978-981-10-1947-0_1

Using multiple devices installed in arrays, cycles can be phased to ensure there is largely constant generation illustrated in Figure 21 delivered by the whole wind farm when there is available wind.

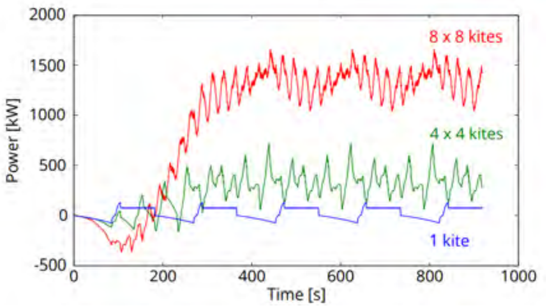


Figure 21 Representation of power generation arrays of 1, 16 and 64 ground-generating reeling tether fixed devices.
(Source: Roland Schmehl)

Onboard generating

These fly-gen devices establish a flight pattern that turns onboard generating devices (small wind turbine) generating electricity and transmitting it down via electrical cables inside the tether at a high voltage (~1kV for 100kW-scale units and up to ~4kV for MW-scale units). Those devices have the ability to provide more continuous power output than ground-generating reeling tether.

Ground-generating– rotary

The rotary motion developed by these devices is used to turn a generator on the ground. The airborne components are passively stable and fitted with small sensors and low power con-trollers for efficiency and manoeuvres.

The major component of a Kite Turbine works as a wide tensile shaft to transmit torque from autogyro rotation. Kite Turbines have relatively short tethers and typically operate at lower altitudes than other AWE devices.

The rotors exploit multiple simple lightweight kite blades tied around carbon rings. Multiple rotors are then stacked together modularly in a conic network.

The top of the network is guided and lifted from above by a lifting kite and from below by a backline launch and recovery robot.

An extension of this concept proposes scaling via a network of networks pattern which will remove the need for back-line robots.

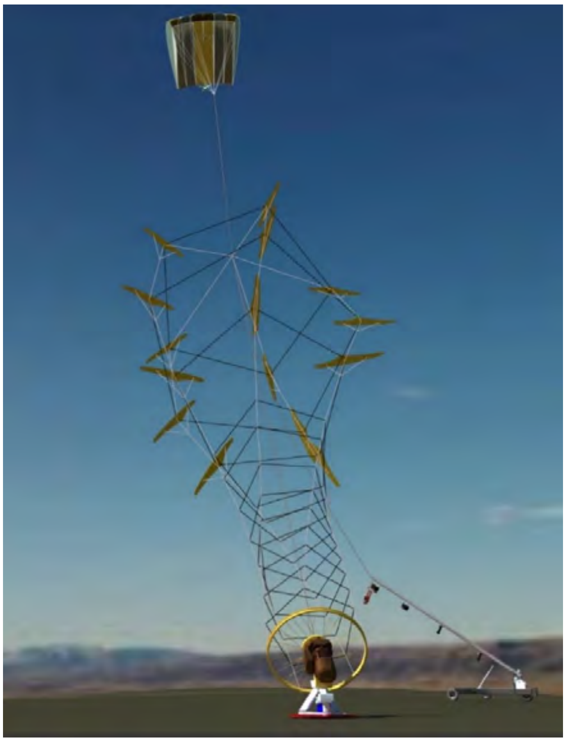


Figure 22 Ground-generating rotary device design.
(Source: Windswept and Interesting).

Appendix B Onshore spatial LCOE

More detail on the spatial analysis of LCOE for AWE, established wind, solar PV and diesel generators are as presented here.

Assumptions

Global assumptions

Several necessary simplifications have been taken to support this global analysis:

- Real (2022) prices
- Onshore locations only
- Design and costs of technologies installed anywhere in the world are constant irrespective of local market conditions (including actual local labour costs, supply chain capability etc.).
- Wind speed, diesel fuel costs and solar irradiation inputs vary by location
- The site conditions are assumed the same across the globe being able to accommodate the 4 different technologies, and
- 500kW systems for all technologies to enable a like-for-like comparison for project size over time.

Technology assumptions

Solar PV

- 500kW array of stationary, ground mounted, polycrystalline Silicon PV cells
- Baseline costs for CAPEX and OPEX from "Future renewable energy costs: solar photovoltaics"
- Cost trends from applied from "Solar PV powering through to 2030"
- Solar data from "GLOBAL SOLAR ATLAS"
- WACC of 6% (lower than wind technologies reflecting its simpler installation and operation)
- 20-year project lifetime

As an indication for the LCOE for solar in Seville Spain it is 49 €/MWh in 2030, 44.5 €/MWh in 2040 and 41.5 €/MWh in 2050.

AWE

- AWE 500 kW system
- Cost from AWE LCOE model using inputs confirmed with Airborne Wind Europe members to be a representative system for 2025.
- WACC is 7.5%
- 20-year project lifetime

Established wind

- Single horizontal axis wind turbine (HAWT) 500kW. Note this size is to enable a like-for-like comparison for the same project size over time – larger rated turbines are and will be more cost effective.
- Capital and operational costs from BVG Associates inhouse HAWT LCOE model
- Cost scaling to 2030, 2040 and 2050 use the projected costs in the BVG Associates in-house HAWT LCOE model
- WACC is 7.5%
- 20-year project lifetime

Diesel Generation

- Assumes a 500kW Diesel system.
- Diesel capital and operational Costs taken from "Lazards LCOE Cost of Energy Analysis version 10.0" [xxxii]
- Diesel fuel cost data uses 2016 global cost on a country-by-country basis from World bank Diesel cost trend is extrapolated from historic trends in Diesel price from 1990 to 2016. This is used to project commodity costs to 2030, 2040 and 2050.
- WACC of 5%
- 7-year lifetime

[xxix] https://c2e2.unepdtu.org/kms_object/future-renewable-energy-costs-solar-photovoltaics-how-technology-innovation-is-anticipated-to-reduce-the-cost-of-energy-from-european-photovoltaic-installations/, Accessed 06/06/22

[xxx] https://www.dnv.com/to2030/technology/solar-pv-powering-through-to-2030.html Accessed 03/05/22

[xxxi] https://globalsolaratlas.info/map?c=19.47695,-76.289063,2 Accessed 15/04/22

[xxxii] https://www.lazard.com/perspective/levelized-cost-of-energy-analysis-100/

[xxxiii] https://data.worldbank.org/indicator/EP.PMP.DESL.CD Accessed 8/4/22

LCOE results for 2030

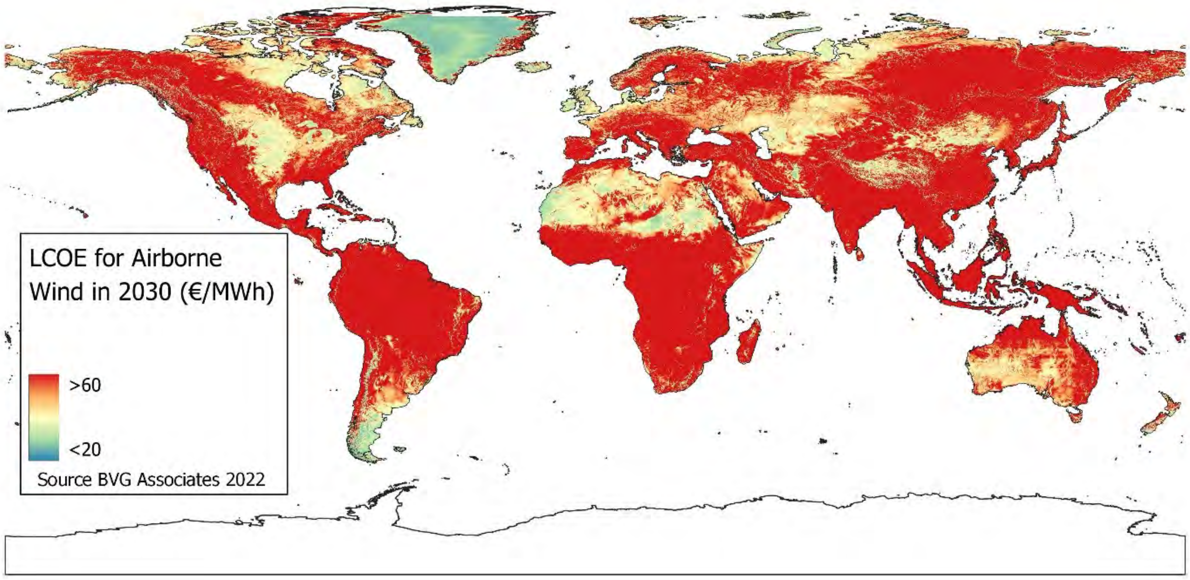


Figure 23 Global LCOE for representative AWE system in 2030.

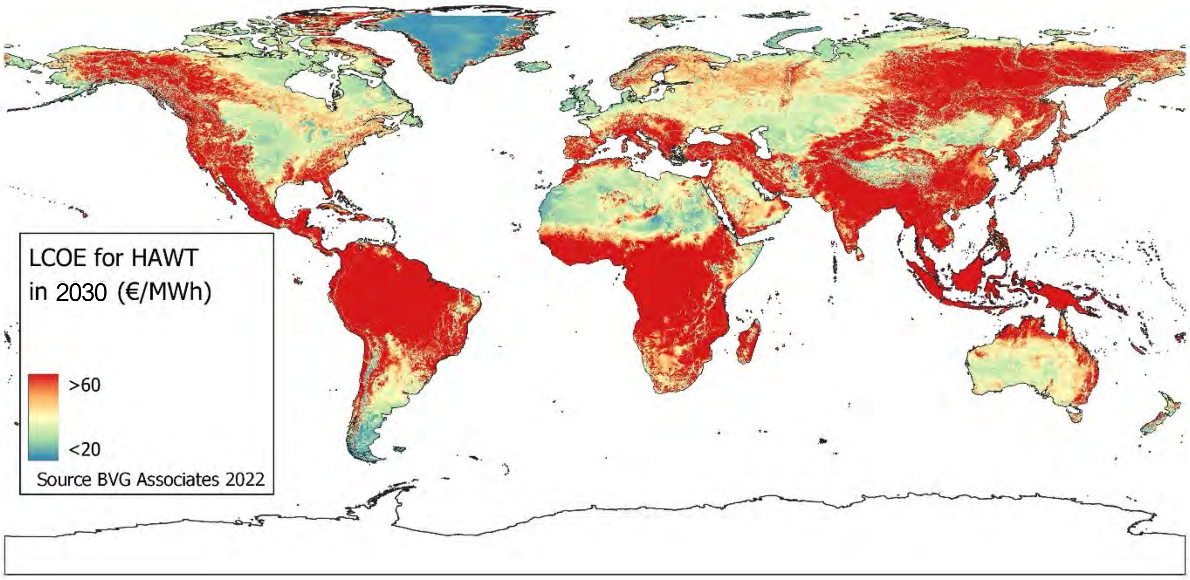


Figure 24 Global LCOE for representative established wind system in 2030.

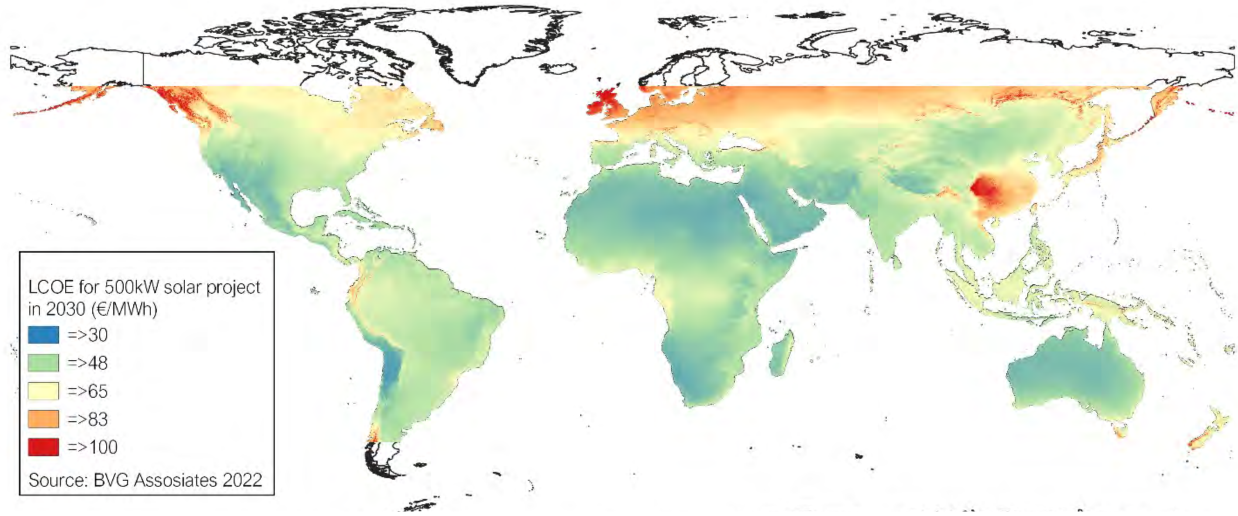


Figure 25 Global LCOE for solar PV generation in 2030 (Arctic regions excluded due to lack of reliable data).

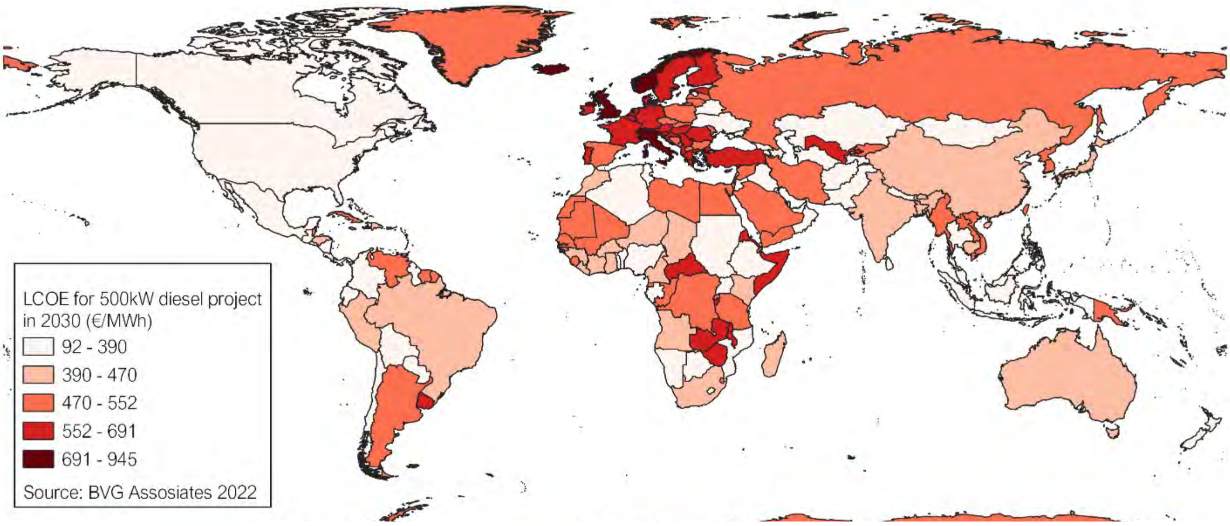


Figure 26 Global LCOE for diesel generators in 2030.

LCOE results for 2040

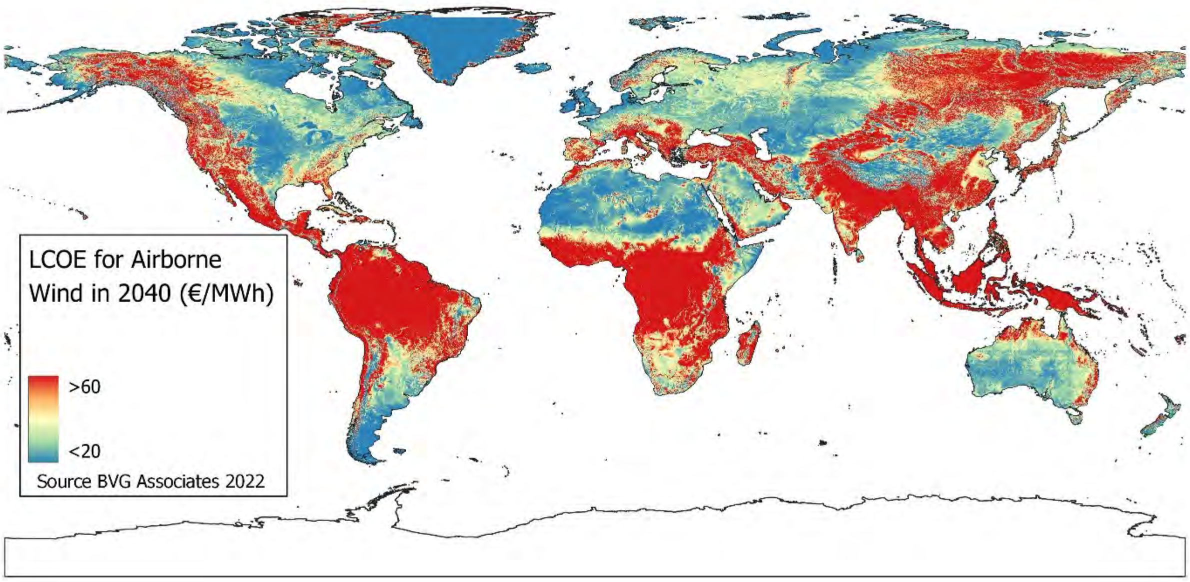


Figure 27 Global LCOE for representative AWE system in 2040.

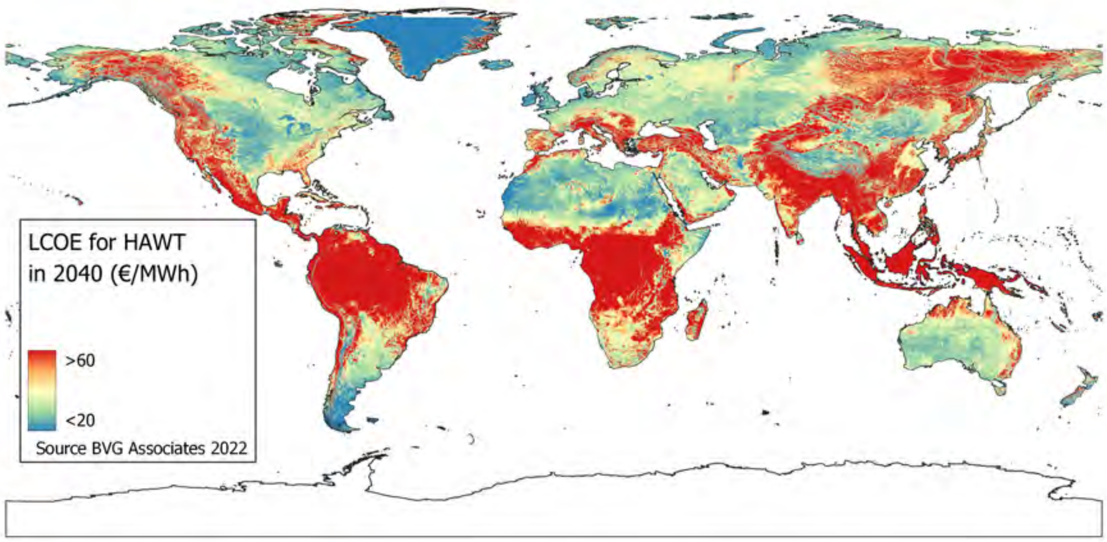


Figure 28 Global LCOE for representative established wind system in 2040.

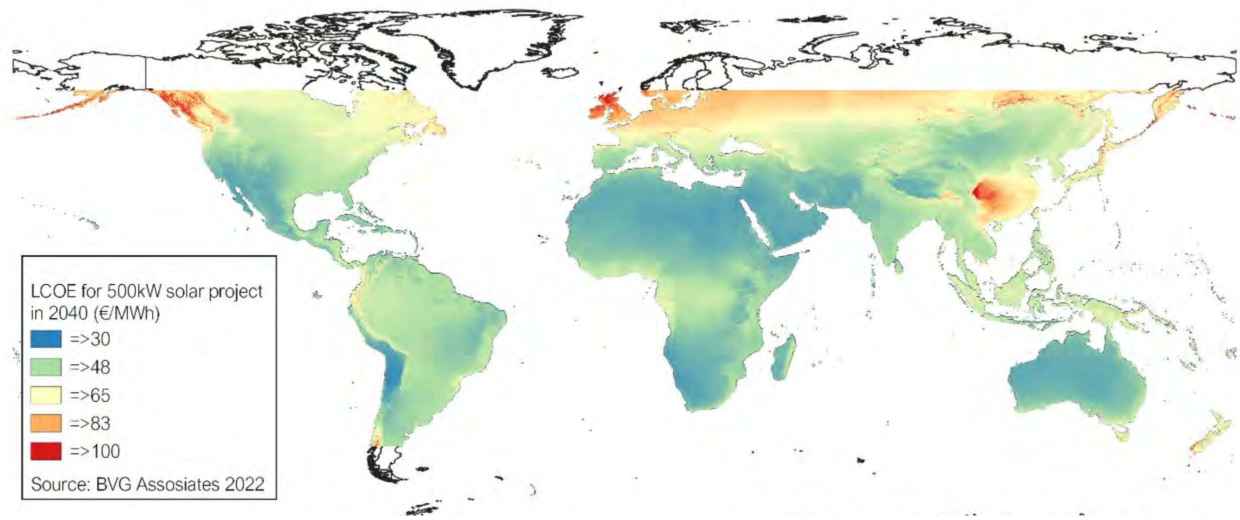


Figure 29 Global LCOE for solar PV generation in 2040 (Arctic regions excluded due to lack of reliable data).

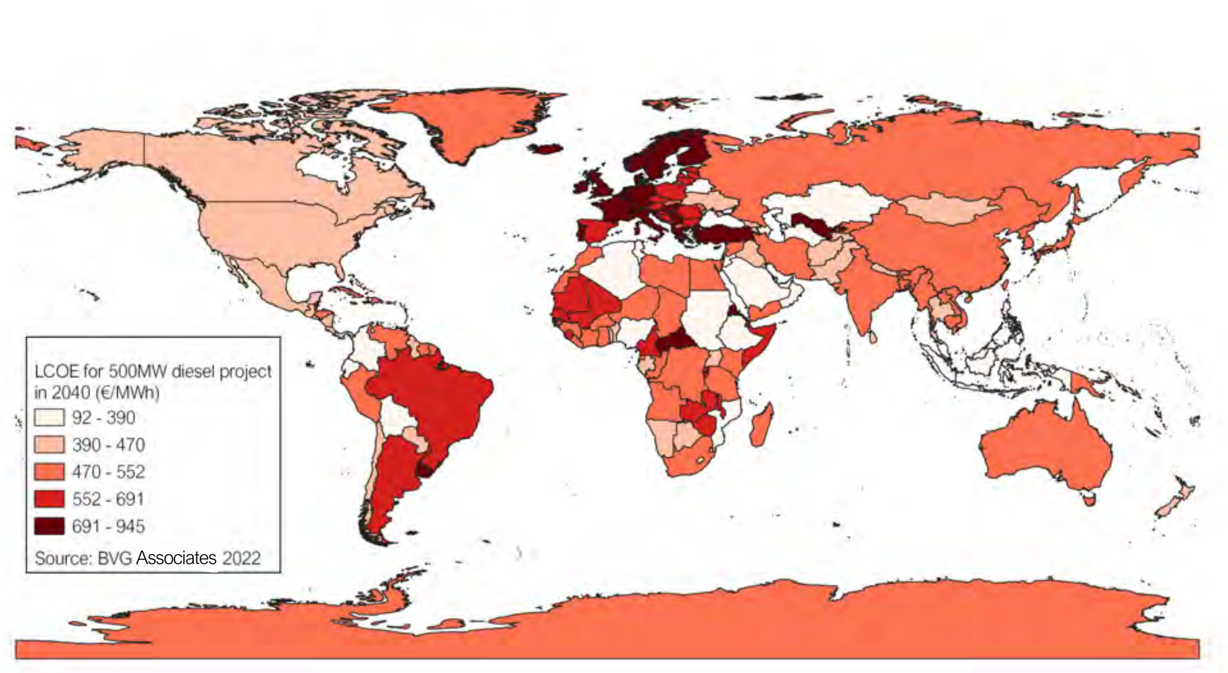


Figure 30 Global LCOE for diesel generators in 2040.

LCOE results for 2050

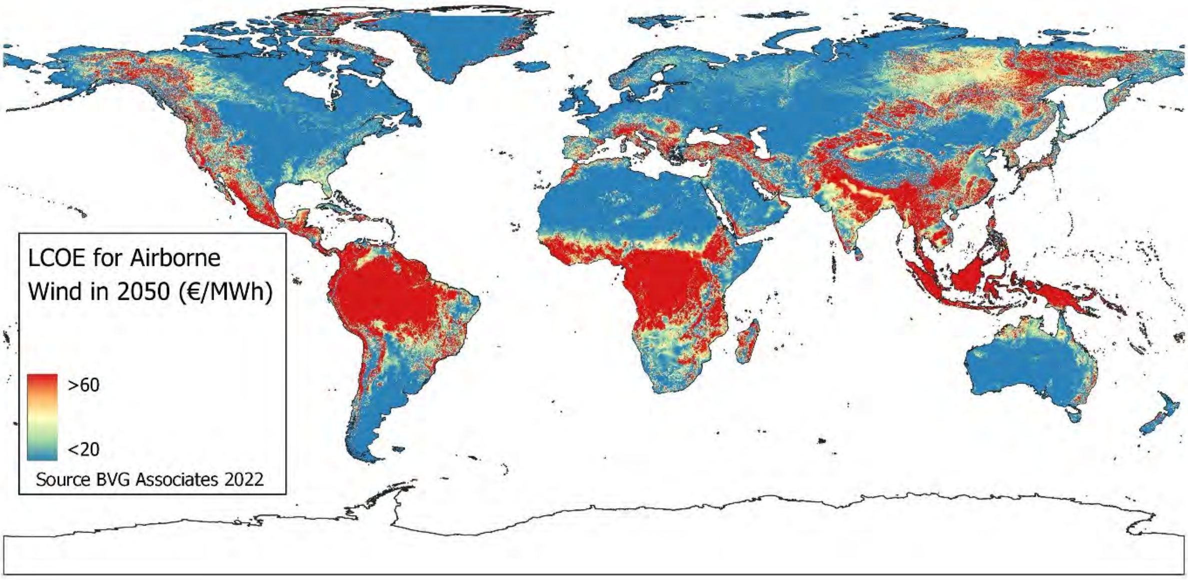


Figure 31 Global LCOE for representative AWE system in 2050.

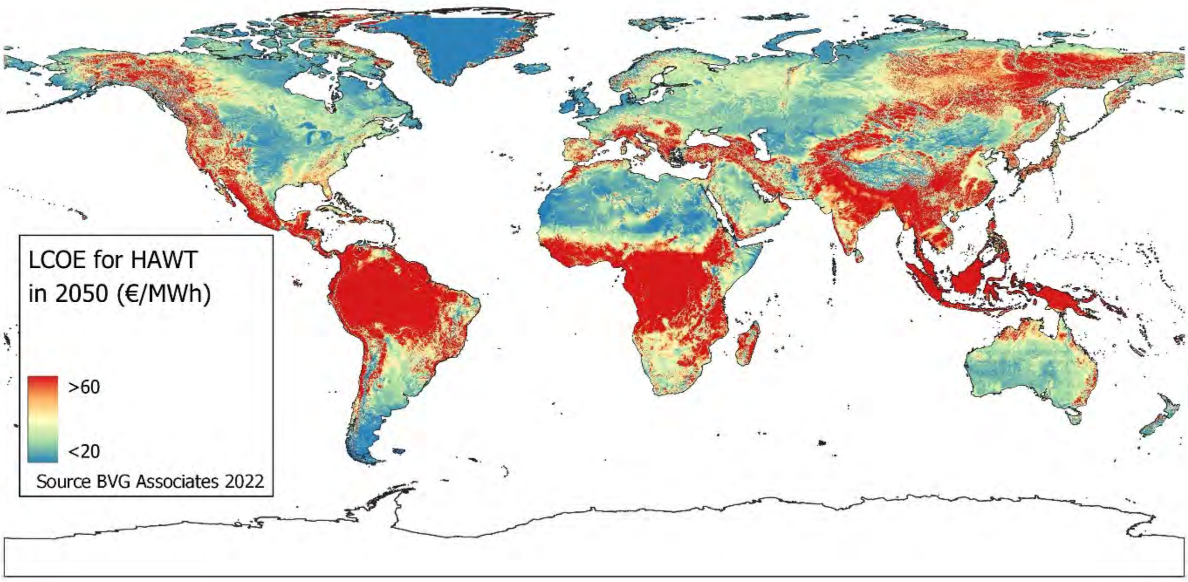


Figure 32 Global LCOE for representative established wind system in 2050.

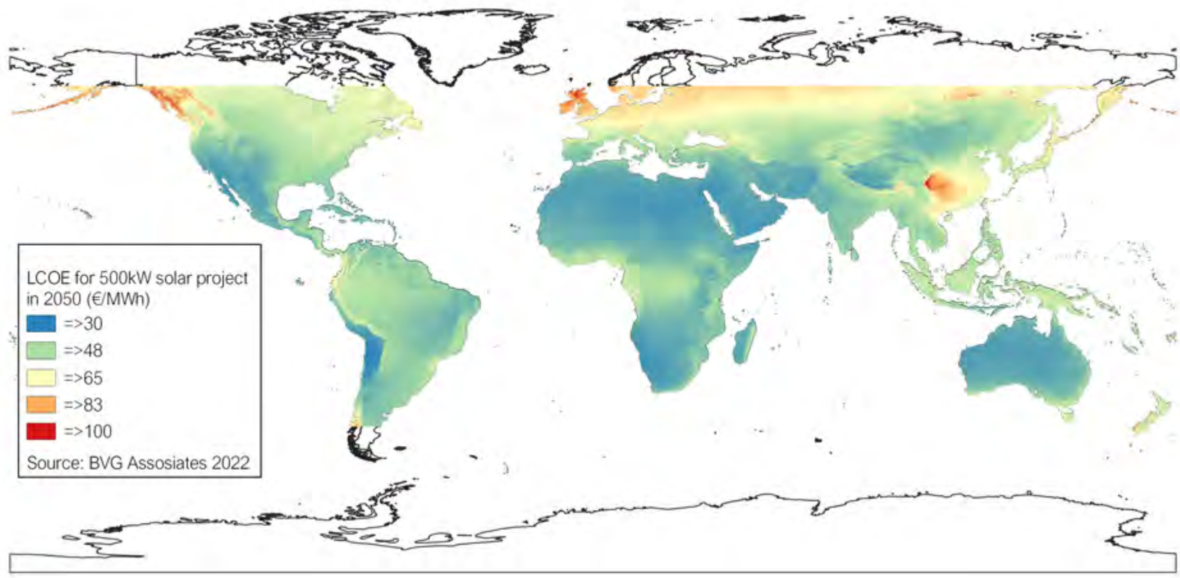


Figure 33 Global LCOE for solar PV generation in 2050 (Arctic regions excluded due to lack of reliable data).

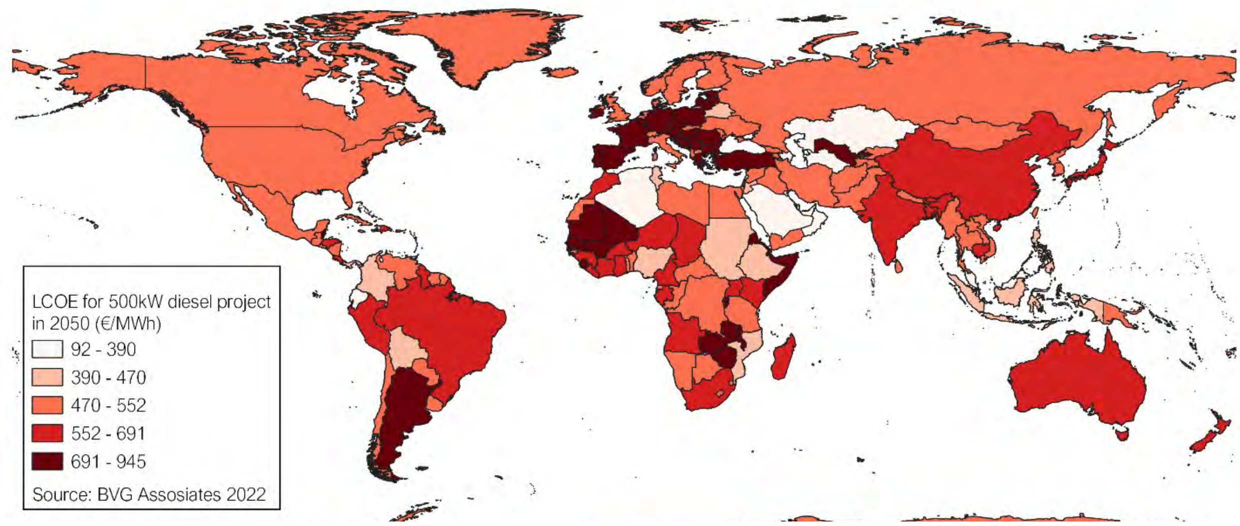


Figure 34 Global LCOE for diesel generators in 2050.

About BVG Associates

BVG Associates is an independent renewable energy consultancy focussing on wind, wave and tidal, and energy systems.

Our clients choose us when they want to do new things, think in new ways and solve tough problems. Our expertise covers the business, economics and technology of renewable energy generation systems. We're dedicated to helping our clients establish renewable energy generation as a major, responsible and cost-effective part of a sustainable global energy mix. Our knowledge, hands-on experience and industry understanding enables us to deliver you excellence in guiding your business and technologies to meet market needs.

- BVG Associates was formed in 2006 at the start of the offshore wind industry.
- We have a global client base, including customers of all sizes in Europe, North America, South America, Asia and Australia.
- Our highly experienced team has an average of over 10 years' experience in renewable energy.
- Most of our work is advising private clients investing in manufacturing, technology and renewable energy projects.
- We've also published many landmark reports on the future of the industry, cost of energy and supply chain.