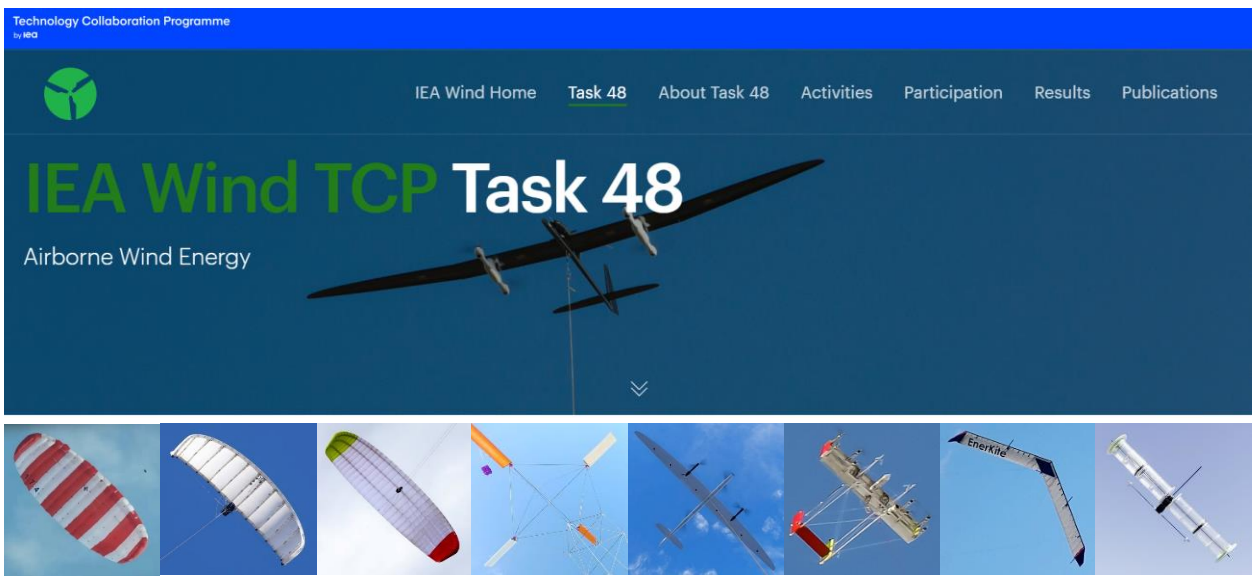
IEA Wind TCP

IEA Wind Task 48 Final Technical Report

Airborne Wind Energy



Date: 3 November 2025

Operating Agent: Kristian Petrick / Stefanie Thoms, Airborne Wind Europe

Contents

1 Introduction: Background and goals 6
1.1 Introduction 6
1.2 Goal 6
1.3 Dissemination 7
Workplan, deliverables 8
1.4 Workplan 8
1.5 Deliverables and milestones 8
2 WP1 Resource potential and markets 10
2.1 D1.1 AEP predictions for selected sites in Europe and US 10
2.1.1 AWERA Tool 10
2.1.2 Energy system perspective to floating wind turbines and AWE in The North Sea region 10
2.2 D1.2 AEP prediction toolchain documentation 11
2.2.1 Sizing of Hybrid Power Systems for Off-Grid Applications Using Airborne Wind Energy 11
2.2.2 Value-Driven System Design of Utility-Scale Airborne Wind Energy 11
2.3 D1.3 Global high-altitude wind resource atlas 12
2.3.1 Wind Resource Maps for Europe 12
2.3.2 Kite as a sensor: wind and state estimation in tethered f lying systems 14
2.4 D1.4 Roadmap: Recommendations on AWE entry-markets 15
2.4.1 Country Mapping 15
2.4.2 GIS Studies on potential AWE sites 15
2.4.3 World map of test, demonstration and commercial AWE sites 16
3 WP2 Reference models, tools and metrics 19
3.1 D2.1 Report and Common definitions of metrics and KPIs and gap analysis 19
3.1.1 Glossary 19
3.1.2 AWE Technology Performance Levels 19
3.2 D2.2 Online dissemination platform Reference model(s) 19
3.2.1 MegAWES reference model and simulation framework 19
3.2.2 Soft kite and other simulation models 20
3.2.3 Fechner Julia Kite Power tools 21
3.2.4 Impact of wind profiles on ground-generation AWES performance 21
3.2.5 Validated power curve 22
3.3 D2.3 Centralized design tool database 22
3.3.1 Reference Economic Model 23
3.3.2 Other works on design tools 23
3.4 D2.4 Validation of simulations and upscaling assumptions 24

3.4.1 Reference kite V3 24
3.4.2 Swinging motion of a kite with suspended control unit flying turning manoeuvres 24
4 WP3 Safety and regulation 26
4.1 D3.1 Whitepaper on AWES safety 26
4.2 D3.2 Concept of operations (CONOPS) and SORA guidelines 26
4.3 D. 3.3 U-Space integration concept 28
4.4 D3.4 Overview of design concepts for safe automatic operation 28
5 WP4 Social Acceptance and environmental impacts 30
5.1 D4. LCA for AWE 30
5.2 D4.2 Repository of surveys/studies on social acceptance & impacts on birds/bats 32
5.2.1 Literature review 32
5.2.1 Survey and interviews of residents 32
5.2.2 Exploring Noise Annoyance and Sound Quality for AWE systems: A Listening Experiment 32
5.2.3 GrowFlowFly 32
5.2.4 Repository of environmental impact studies 33
5.3 D4.3 Guidelines for site selection and environmental impact mitigation measures 33
5.4 D4.4 Circular economy / cradle-to-cradle aspects for AWE, incl. design process 34
6 WP5 AWES Architectures 35
6.1 D5.1 Design space representation 35
6.2 D5.2 Application / market specific recommendations / Performance Criteria 35
6.3 D5.3 Oversight on AWES R&D state, trends and needs 36
6.3.1 BVG White Paper 36
6.3.2 Autonomous Airborne Wind Energy systems: accomplishments and challenges 36
6.4 D5.4 Definition of a portal for identifying AWES development potential 36
7 Cooperation with other IEA Tasks 37
8 Conclusions and recommendations 38
8.1 Conclusions 38
8.1.1 Achievements of Task 48 38
8.1.2 Status of the Airborne wind energy (AWE) sector and the need for Task 48 38
8.2 Recommendations and future work 39
9 Publications, presentations, dissemination 40

Figures

Figure 1: Task 48 Work Packages of 1st term ... 6
Figure 2: Airborne Wind Energy Resource Analysis Tool AWERA (AWEC 2021 book of abstracts). ... 10
Figure 3: The potential role of airborne and floating wind in the North Sea region. Source: Vos et al. 2024 ... 11
Figure 4: Flowchart of the system design framework. Source: Joshi (2023) ... 12
Figure 5: Minimum LCoE trend for the onshore business case. Source: Joshi 2023. ... 12
Figure 6: Wind Resource maps for selected European countries. Source: Thimm 2022. ... 13
Figure 7: Kite as a sensor. Source: TUD ... 14
Figure 8: Test flight time series comparison of wind estimates from different EKF configurations, including a minimal sensor setup and three variants with additional inputs, against lidar observations and ground-based measurements. ... 14
Figure 9: Example of evaluation of country readiness for AWE ... 15
Figure 10: Potential AWE sites in Germany, France, Ireland and the Netherlands for the respective base case. Source: Coca 2023, Coca 2024, Moutel 2024, Moutel 2025 ... 16
Figure 11: Map of AWE sites. Source: Airborne Wind Europe. ... 17
Figure 12: Test sites in Europe and site-specific data ... 18
Figure 13: Technology readiness levels (TRLs) and technology performance levels (TPLs) of the main technology development status groups (left) across the global AWE sector. Source: Weber et al. 2021. https://docs.nrel.gov/docs/fy21osti/79992.pdf ... 19
Figure 14: Computer rendering of the MegAWES reference model ... 20
Figure 15: Julia Kite Power Tools. Source: ABB Delft / Uwe Fechner. ... 21
Figure 16: Onshore and offshore power curve approxiamations. Source: Sommerfeld et al. 2023. ... 22
Figure 17: Validated power curve. Source. SkySails Power 2024 ... 22
Figure 18: Flowchart representing the inputs and outputs of the developed economic model. Source: Joshi 2024 ... 23
Figure 19: Optimal design of windplanes. Source: Trevisi 2024 ... 23
Figure 20: TUD V3 kite. Source: TUD. ... 24
Figure 21: Swinging motion of a kite with suspended control unit. Source: Schelbergen et al. 2024. ... 25
Figure 22: Survey: Air risk mitigation measures. Source: Houle 2023 ... 27
Figure 23: Survey: Ground risk mitigation measures. Source: Houle 2023 ... 27
Figure 24: Definition of the operational volume for AWES and related terminology. Source: Salma et al. 2023. ... 28
Figure 25: First two AWE-specific IEC 61400 standards ... 29
Figure 26: LCA Analysis: Global Warming Potential of an AWE system compared to a Horizontal Axis Wind Turbine (HAWT) system ... 30
Figure 27: Propsective LCA. Source: Treyer 2024. ... 31
Figure 28: JustWind4All Energy Read. Source: Airborne Wind Europe 2025. ... 33
Figure 29: JustWind4All Energy Read: Summary of guidelines. Source: Airborne Wind Europe 2025. ... 34
Figure 30: AWES Type Classification / Design Space ... 35
Figure 31: Global LCOE for representative AWE system versus cheapest alternative in 2040 for 500kW project. Source: BVG 2022. ... 36
Figure 32: Task 48 Work Programme of 2nd term ... 39

Tables

Table 1: Work Packages 8
Table 2: Deliverables and Milestones 8
Table 3: LCA studies on AWE 30

1 Introduction: Background and goals

1.1 Introduction

This report describes the main results of the IEA Wind Task 48 on Airborne Wind Energy (AWE). The first term of Task 48 was kicked off in October 2021 and ended in September 2025.

The following countries and parties participated in the first term of Task 48: BE, CH, DE, DK, ES, IE, IT, NO, NL, UK, US.

1.2 Goal

The objective of Task 48 is to tackle various of the specific challenges for this new technology on a global level by addressing and including stakeholders who are not primarily AWE developers, i.e., policy makers, authorities, regulators and other wind energy and technology experts.

A key benefit of the IEA Task on AWE is that it opens the scope of collaboration to the whole world; it will thus foster a truly international exchange of expertise, produce and gather new data and information, allow for joint learning, as well as accelerate the development of AWE technology and thus its impact on the international energy sector.

Expected results were:

- Enhanced international collaboration and coordination in the field of AWE to leverage the work being done in the AWE sector.
- Studies and reports in five focus areas (work packages, WPs).
- Updated library of Task publications, collaborative journal articles and list of relevant studies and other publications
- Open-source dynamic models, with corresponding documentation and training opportunities, for common use in AWE research and development.

The following graphic provides an overview of the 5 WPs:

WP0: Task coordination	WP1: Resource potential and markets	WP2: Reference models, tools and metrics	WP3: Safety and regulation	WP4: Social Acceptance	WP5: AWES architectures
• Organisation & management of Task • Communication • Website • Dissemination	• AEP prediction for selected sites & toolchain documentation • Global high-altitude wind resource atlas • Recommendation on AWE entry-markets	• Common definition of metrics and KPIs • Joint reference model(s) • Centralized design tool • Simulation vs. test flights comparison	• Concept of operations and risk assessment • Airspace integration concept • Benchmarking concepts for safe automatic operation	• Life-Cycle Analysis • Literatur review • Conducting surveys and studies • Guidelines for site selection, sound measurement and impact mitigation • Circular Economy	• Design space representation • Market specific deployment recommendations • AWES R&D state, trends and needs • Portal for AWES engagement and development potential
• Task reporting • Communication outputs	• AEP prediction toolchain • Economic metrics	• Definitions • Centralized design tool database	• Whitepaper on AWES safety	• LCA of AWE • Repository of surveys & studies	• Guidelines

Figure 1: Task 48 Work Packages of 1st term

1.3 Dissemination

The following organisations participated in Task 48. Participants have disseminated project results through their respective networks:

Country
Participants
BE
Airborne Wind Europe
SABCA
University of Ghent
CA
Concordia University
CH
EPFL
ETH Zürich
PSI
Swiss Federal Office of Energy
Swiss FOCA
twingtec AG
UASolutions
DE
Enerkite GmbH
FGW
Fraunhofer ISI
kiteKRAFT
Leibniz University of Hannover
RWE
RWTH Aachen
TU Munich
SkySails Power GmbH
Uni Bonn
University of Applied Sciences Munich
University of Bonn
University of Freiburg
University of Halle
University of Stuttgart
DK
DTU
ES
CT Ingenieros
Siemens Gamesa
someAWE
UC3M
FR
Laminak
Wind Fisher
IE
Irishrail
MaREI Research Centre, University College Cork
Mayo County Council
RWE
University of Limerick
IRL
SEAI
Blue Wise Marine
University College Cork
IT
Kitenergy
Politecnico di Milano
Politecnico di Milano/ TU Delft
NL
aenarete
Mozaero/Fuchszeug
Kitepower/ enevate
TNO Wind (formerly ECN)
TU Delft
NO
Kitemill AS
NTNU Trondheim
University of Bergen
UK
ORE Catapult
University of Strathclyde
Windswept
US
Colorado State University
University of Michigan
Mail.Uc
North Carolina State University
NREL
SNL
UCSB
University of Dayton
University of Washington
Windlift
Worcester Polytechnic Institute

Further dissemination activities are described in the Final Management Report of Term 1.

Workplan, deliverables

1.4 Workplan

The workplan consisted of 5 work packages:

Table 1: Work Packages

No.	Work Package Name	Lead Organisation	Deliverables	Milestones
WP0	Management and dissemination	Airborne Wind Europe (AWEU) (BE)	D0.1 – D0.5	M0.1 – M0.2
WP1	Resource potential and markets	TU Delft (NL), University of Bonn (DE)	D1.1 - D1.4	M1.1 - M1.3
WP2	Reference models, tools and metrics	NC State University (US), TU Delft (NL)	D2.1 – D2.4	M2.1 – M2.3
WP3	Safety and regulation	RWTH Aachen University (DE)	D3.1 – D3.4	M3.1 – M3.2
WP4	Social Acceptance	AWEU (BE)	D4.1 – D4.4	M4.1 – M4.2
WP5	AWES Architectures	someAWE Labs (ES), AWEU (BE)	D5.1 – D5.4	M5.1 – M5.2

1.5 Deliverables and milestones

On overview of the deliverables and milestones and their respective status are given in the following table:

Table 2: Deliverables and Milestones

No.	Deliverable	Due date	Status 10/25
WP0	**Management and dissemination**		**WP0**
D.01	Website Launch	Mar-22	Done
D0.2-0.4	Annual Progress Reports to ExCo	annual	Done
D.05	Final Report	Nov-25	Done
M0.1	Task Kick-off Meeting	Oct-21	Done
M0.2	Final Meeting	Nov-25	n/a
WP1	**Resource potential and markets**		**WP1**
D1.1	AEP predictions for selected sites in Europe and US	Jun-23	Done
D1.2	AEP prediction toolchain documentation	Mar-24	Done
D1.3	Global high-altitude wind resource atlas / wind measurements	Jun-24	Partially done
D1.4	Roadmap: Recommendations on AWE entry-markets	Sep-25	Done
M1.1	WP kick-off meeting	Dec-21	Done
M1.2	AEP prediction toolchain published	Mar-24	Done
M1.3	Economic metrics for AWE published	Mar-25	Done
WP2	**Reference models, tools and metrics**		**WP2**
D2.1	Report and Common definitions of metrics and KPIs and gap analysis	Dec-23	Done
D2.2	Online dissemination platform Reference model(s)	Mar-25	Done

No.	Deliverable	Due date	Status 10/25
D2.3	Centralized design tool database	Jun-24	Done
D2.4	Comparison of simulation and test flight data, validation of simulations and upscaling assumptions	Sep-25	Done
M2.1	WP kick-off meeting	Dec-21	Done
M2.2	Completion of initial centralized design tool database	Jun-23	Partially done
M2.3	Workshop to provide critical discussion and training on AWE design tools	Dec-24	Done
WP3	**Safety and regulation**		**WP3**
D3.1	Whitepaper on AWES safety	Mar-23	Done
D3.2	Concept of operations (CONOPS) and SORA guidelines	Sep-24	Done
D3.3	U-Space integration concept	Mar-25	n/a
D3.4	Overview of design concepts for safe automatic operation	Sep-25	Partially done
M3.1	Whitepaper on AWES safety published	Mar-23	Done
M3.2	Event with airsafety stakeholders to discuss findings and deliverables	Dec-24	Partially done
WP4	**Social Acceptance**		**WP4**
D4.1	LCA for AWE and conclusions	Jun-22	Done
D4.2	Repository of surveys/studies on social acceptance & impacts on birds/bats	Jun-25	Done
D4.3	Guidelines for site selection, noise measurement and environmental impact mitigation measures	Sep-24	Done
D4.4	Circular economy / cradle-to-cradle aspects for AWE, incl. design process	Sep-25	Partially done
M4.1	LCA for AWE	Jun-22	Done
M4.2	Event with environmental and societal stakeholders to discuss findings and deliverables	Mar-25	Done
WP5	**AWES Architectures**		**WP5**
D5.1	Design space representation / Archetyes	Mar-23	Done
D5.2	Application / market specific recommendations on AWES deployment / Performance Criteria	Jun-24	Done
D5.3	Oversight on AWES R&D state, trends and needs	Jun-25	Done
D5.4	Definition and specification of a portal for identifying AWES engagement and development potential	Sep-25	n/a
M5.1	Kick-off	Dec-21	Done
M5.2	Final WP meeting	Jun-25	Done

In the following sections, the key results of each deliverable within each work package are given.

Note: Compared to other technical reports of the IEA Wind TCP, the descriptions of the activities under the deliverables is kept relatively short since Task 48 is primarily a task were research activities of the different participating organizations share their insights and discuss them; only a few activities are "genuine collaborative activities" where Task 48 participants are elaborating a joint document. However, there are a few of those as well, e.g. the White Paper on Safe Airspace Integration or the Paper on AWE Architectures.

2 WP1 Resource potential and markets

2.1 D1.1 AEP predictions for selected sites in Europe and US

2.1.1 AWERA Tool

The Airborne Wind Energy Resource Analysis tool AWERA (https://github.com/awegroup/AWERA) was developed for assessing the potential of airborne wind energy systems on large geographical and temporal scales. The tool is the result of the graduation project of University of Bonn student Lavinia Thimm, in collaboration with PhD researcher Mark Schelbergen, TU Delft, who had developed a clustering technique for vertical wind profiles to substantially accelerate AEP calculations and develop insight into how the vertical wind profile affects energy harvesting. The AWERA tool was also used for a site-specific AEP assessment at the Harbour of Rotterdam.

The work was presented in June 2022 in Milan (Thimm et al. 2022).

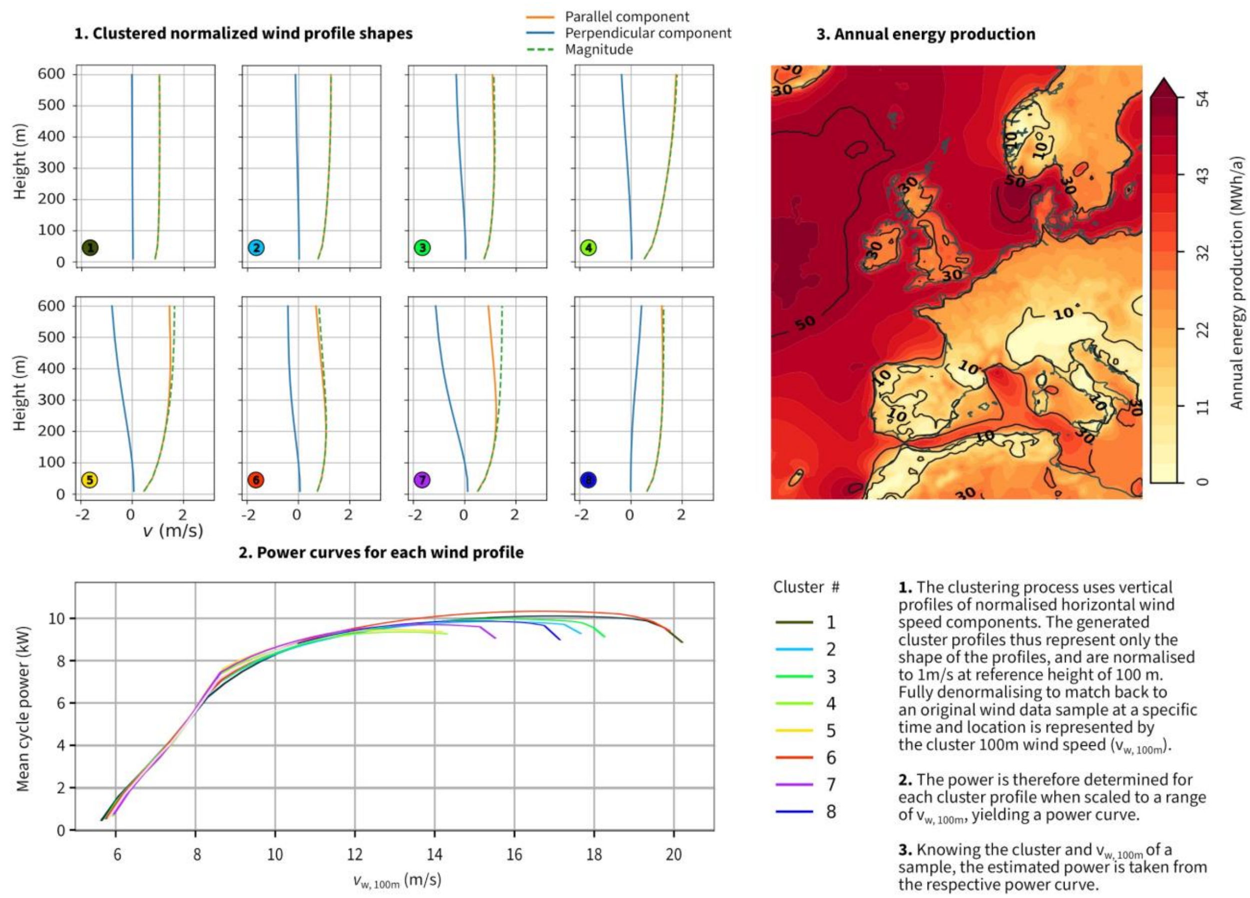


Figure 2: Airborne Wind Energy Resource Analysis Tool AWERA (AWEC 2021 book of abstracts).

2.1.2 Energy system perspective to floating wind turbines and AWE in The North Sea region

A study by TU Delft within the Horizon JustWind4All project investigated "*A whole-energy system perspective to floating wind turbines and airborne wind energy in The North Sea region".* It concluded that AWE has the potential to significantly reduce energy system costs. Further, onshore AWE is the preferred technology, even at higher costs assuming that the spatial capacity density is comparable which needs to be further investigated (Vos et al. 2022).

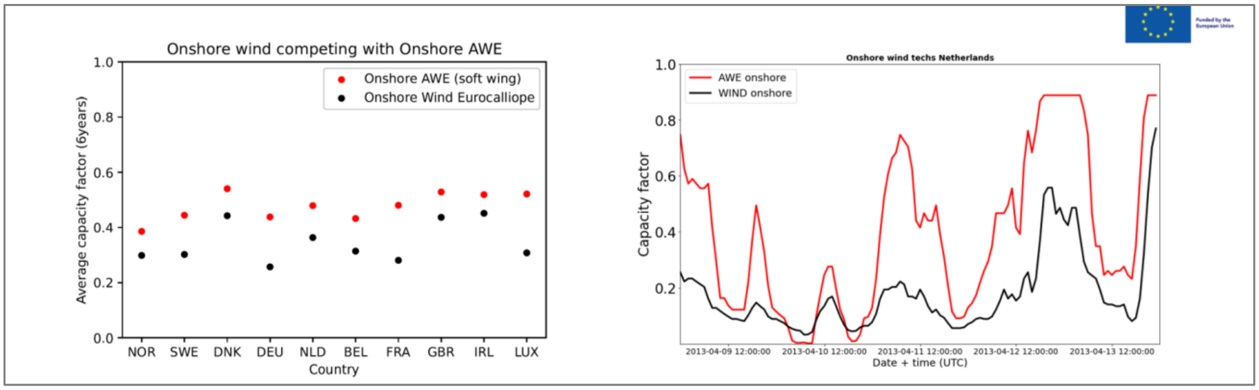


Figure 3: The potential role of airborne and floating wind in the North Sea region. Source: Vos et al. 2024

2.2 D1.2 AEP prediction toolchain documentation

Under this deliverable two papers were published:

2.2.1 Sizing of Hybrid Power Systems for Off-Grid Applications Using Airborne Wind Energy

This paper presents a modelling and sizing framework for off-grid hybrid power systems using airborne wind energy, solar PV, batteries and diesel generators. The framework is based on hourly time-series data of wind resources from the ERA5 reanalysis dataset and solar resources from the National Solar Radiation Database maintained by NREL. For the representation of results, a hypothetical case study of an off-grid military training camp located in Marseille, France, was described. The results show that significant reductions in the cost of electricity were possible by shifting from purely diesel-based electricity generation to ajohn hybrid power system comprising airborne wind energy, solar PV, batteries and diesel.

2.2.2 Value-Driven System Design of Utility-Scale Airborne Wind Energy

By using a computational approach to account for the influence of time-varying electricity prices on the design of airborne wind energy (AWE) systems, the framework combines an analytical performance model, providing the power curve of the system, with a wind resource characterisation based on ERA5 reanalysis data. The resulting annual energy production (AEP) model is coupled with a parametric cost model based on reference prototype data from Ampyx Power B.V. extended by scaling laws.

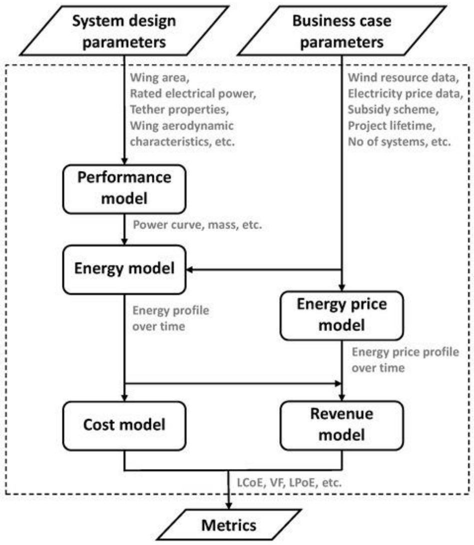


Figure 4: Flowchart of the system design framework. Source: Joshi (2023)

The simulation results confirmed the expected behaviour that the electricity produced at lower wind speeds has a higher value than that produced at higher wind speeds. To account for this electricity price dependency on wind speeds in the design process, an economic metric defined as the levelised profit of energy (LPoE) is proposed. This approach determines the trade-offs between designing a system that minimises cost and designing a system that maximises value.

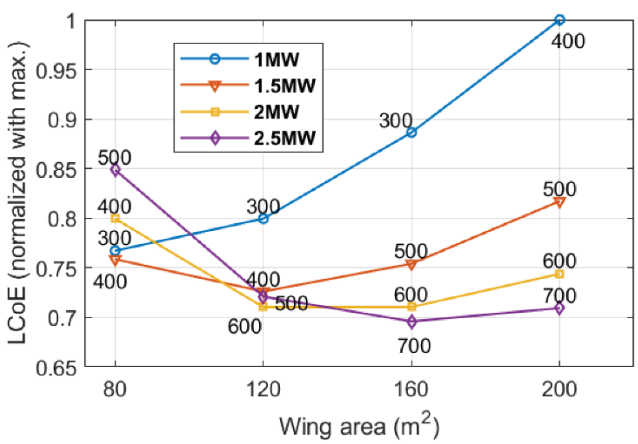


Figure 5: Minimum LCoE trend for the onshore business case. Source: Joshi 2023.

2.3 D1.3 Global high-altitude wind resource atlas

Task 48 did not achieve a global high-altitude wind resource atlas as it was planned at the beginning due to a lack of funding. However, a few activities with regards to wind resources were carried out:

2.3.1 Wind Resource Maps for Europe

Wind resource plots for specific countries were refined and improved by University of Bonn and TU Delft, building on the analysis from Bechtle et al. which was published prior to the establishment of Task 48.

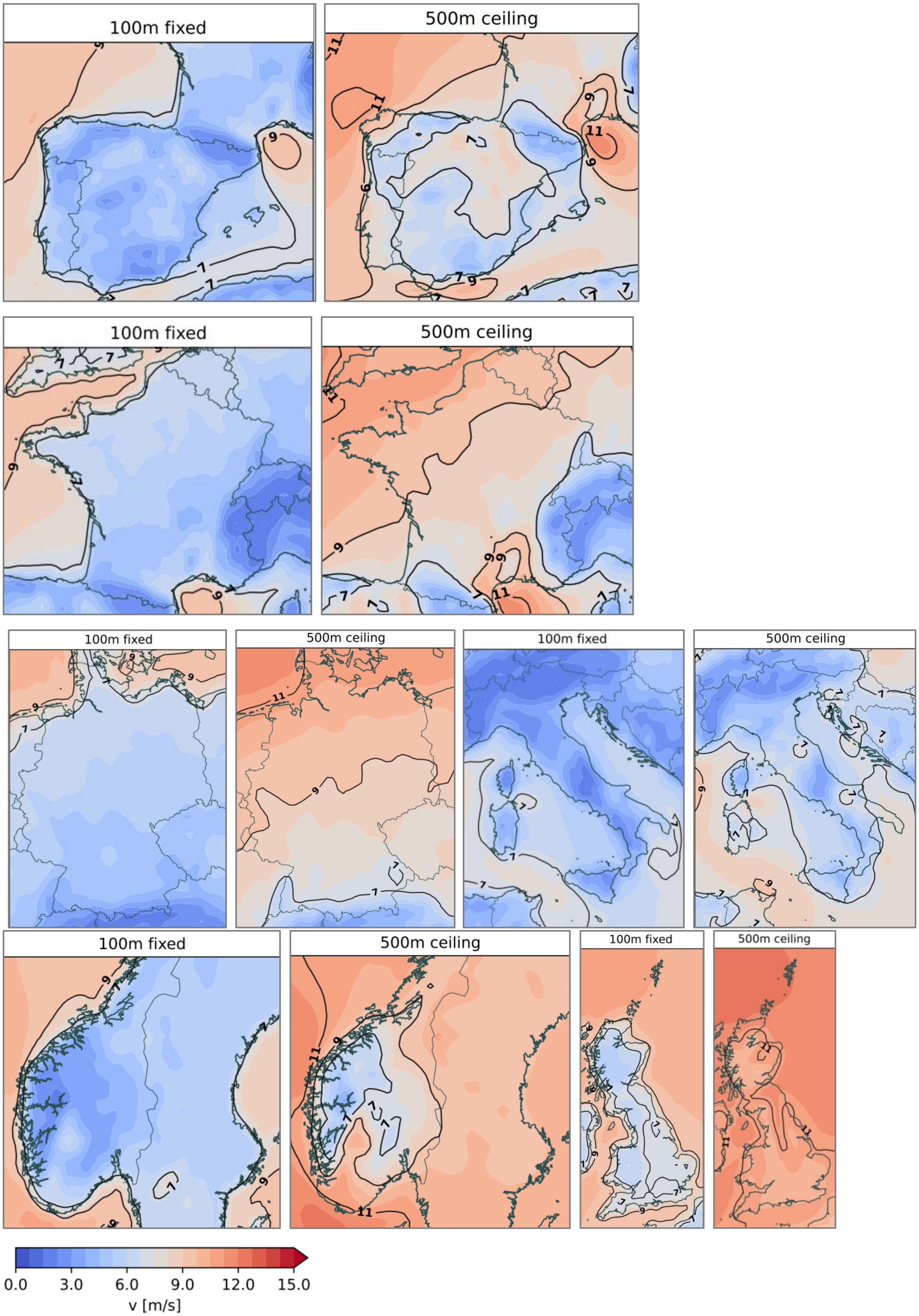


Figure 6: Wind Resource maps for selected European countries. Source: Thimm 2022.

2.3.2 *Kite as a sensor: wind and state estimation in tethered f lying systems*

This paper presents an advanced sensor fusion technique based on an iterated extended Kalman filter (EKF) for state and wind estimation for AWESs.

Figure 7: Kite as a sensor. Source: TUD

By integrating position, velocity, tether force, and reeling speed, this method provides accurate estimations of system dynamics, including kite orientation and tether shape. The estimates of the wind speed and direction are compared to lidar measurements, showing good agreement across various atmospheric conditions.

Figure 8: Test flight time series comparison of wind estimates from different EKF configurations, including a minimal sensor setup and three variants with additional inputs, against lidar observations and ground-based measurements.

The results demonstrate that this approach can effectively capture the transient dynamics of atmospheric wind using sensors typically already present in AWESs, making it suitable for supervisory control strategies and ultimately enhancing energy efficiency and system reliability across diverse atmospheric conditions.

2.4 D1.4 Roadmap: Recommendations on AWE entry-markets

2.4.1 Country Mapping

A Country Mapping draft report was elaborated within the Interreg NWE MegaAWE project as part of the input the entry-markets for AWE. It contains short information on AWE potential, policies, regulation, stakeholders and opportunities as well as a rating which allows for a quick comparison among countries and for identifying areas to be improved, see table below.

Country	DE		IE		ES	
	Score	Comment	Score	Comment	Score	Comment
AWE potential						
Wind resource onshore	4	Good in Northern and Eastern Germany	5	High potential	3	High potential in several regions
Wind resource offshore	3	Some potential	5	Very high potential, incl. floating	4	High potential Northern Coast
Sparsely populated land	3	Rather high persons/km2 but rural areas exist	4	Rather low population/km2	4	Rural areas with few persons/km2
Roll-out opportunities (first sites)	3	Rural areas in Northern and Eastern Germany	4	E.g. self-consumption of farms	5	Especially on islands and rural areas
Government policies						
General RE/wind policy	5	Current government favours RE strongly	2	No support scheme for <500 kW	5	Government favours RE
Concrete AWE policy	1	Not existent	1	Not considered	1	Not considered
R&D / investment support	3	Program in general available	4	SEAI is supportive	3	Programs in general available
Revenue support	1	Not for AWE	1	no, DECC is planning something for small scale	1	Not for AWE
Regulation & Permitting						
Airspace regulation	2	AWE role not clear yet, regions can have own r	4	Potentially favourable because done on natior	0	Probably using drone regulation
Permitting processes	2	Not harmonised	3	lengthy	0	to be checked
Key policy stakeholders						
Parlamentarians	2	Partially informed, no strong supporters yet	1	Not yet involved	1	Not yet involved
Ministry of Energy	2	Informed, minister could be in favour	2	Minister informed	2	Minister informed
Other national ministries /agencies	1	Not yet involved	1	Not yet involved	1	Not yet involved
Regional/local adminstration	2	Partial support where test sites are	2	County Mayo support	2	County Mayo support
AWE stakeholders						
AWE developers/OEMs	4	3 companies, one leading	1	no Irish developer	2	aweSOME, UC3M develop prototypes
IEA Task 48 participants	4	Approx. 15 institutions with interst	3	several participants	3	several participants
Other stakeholders / clients	3	RWE, EnBW potential clients	3	RWE Ireland	1	none
Opportunities						
Test sites	3	3 OEMs with test sites, more investigated	4	County Mayo (RWE test site)	1	not yet
Commercial sites	1	not yet	1	not yet	1	not yet
Industry & jobs	4	In wind and aviation industry	3	SW development, deployment	4	In wind and aviation industry
Total Score						
Average	**2.7**		**2.7**		**2.4**	

Figure 9: Example of evaluation of country readiness for AWE

It is planned to update this analysis in the 2nd term of Task 48.

2.4.2 GIS Studies on potential AWE sites

In collaboration with the Interreg NWE MegaAWE and DEM-AWE projects, detailed GIS-based studies were carried out by BlueWise Marine (IE) and Laminak (FR) to identify potential sites for AWE deployment in Germany, Ireland, the Netherlands and France. It is planned to further refine the methodology and to apply it to other countries like Spain and Norway. The access to reliable data is crucial in order to select the appropriate exclusion criteria.

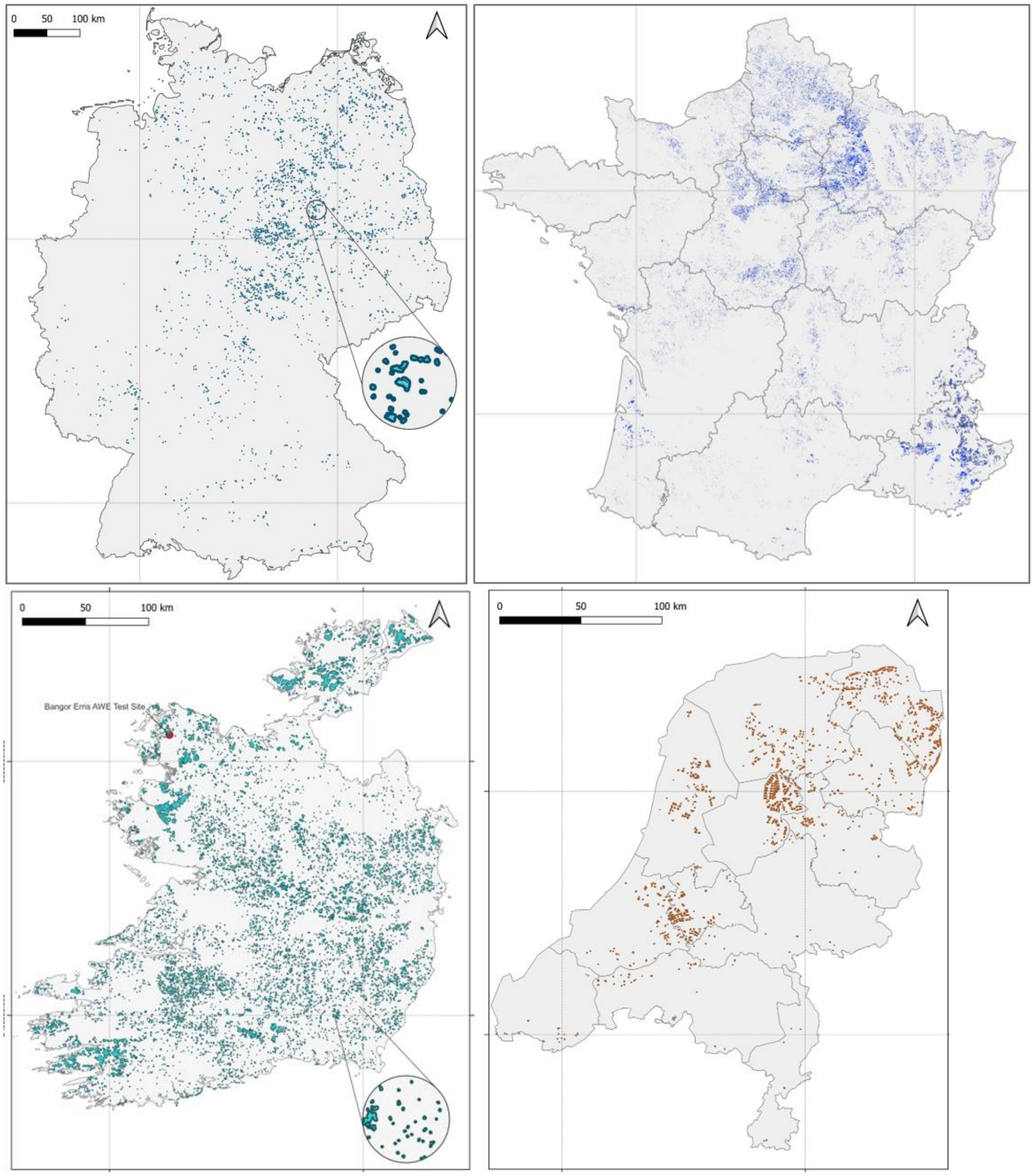


Figure 10: Potential AWE sites in Germany, France, Ireland and the Netherlands for the respective base case. Source: Coca 2023, Coca 2024, Moutel 2024, Moutel 2025

The site assessment analyses have been picked up by industry players in conversations with policy makers on international and national level to demonstrate the vast potential of AWE in Europe.

2.4.3 World map of test, demonstration and commercial AWE sites

Under Task 48 the AWE test, demonstration and commercial sites have been mapped. They are represented according to their status in operation, planned or vacant.

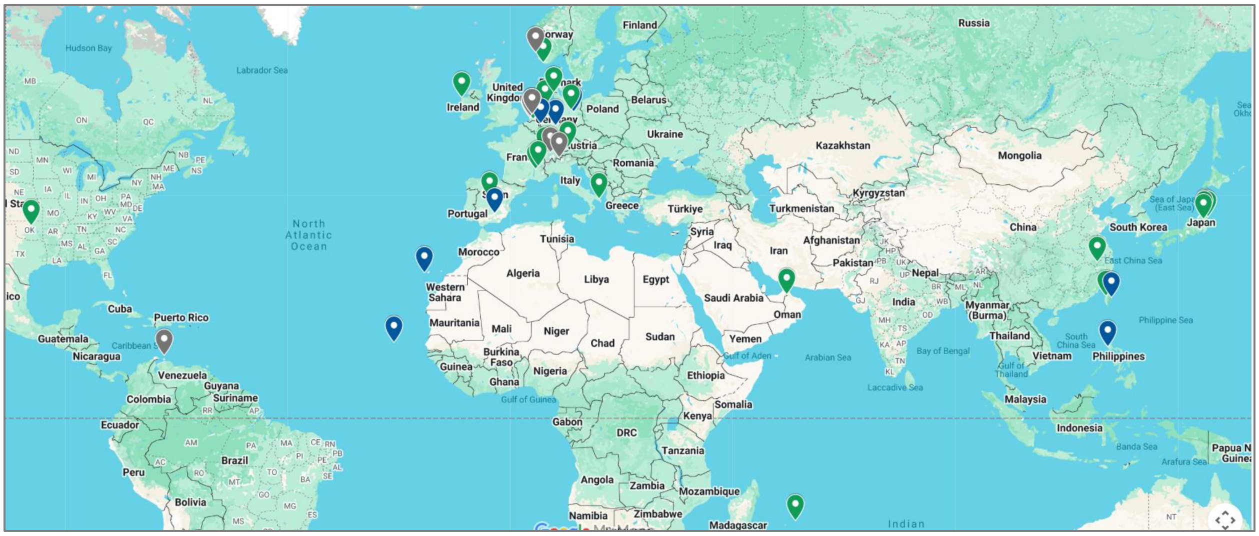


Figure 11: Map of AWE sites. Source: Airborne Wind Europe.

Apart from the location and status, a number of other data were requested to be provided by AWE companies:

- Latitude; Longitude; Name; Country; Status; Start operation; End operation; Site operator; User; Type; Description; Permit to fly: Validity country code; "In (O)peration, (P)lanned, (V)acant";
- Operation permit type; Permit issuing authority; SORA required; Line of Sight; NOTAM?; Permitted altitude [m]; (P)ilot/op. Required; (N)ight flight permitted,; Full (A)utonomy permitted; Date of 1st flight permit issued (MM/YY); Permit validity date (MM/YY); Permit extension possible?;
- Air risk mitigation: (R)estricted flight zone, (D)anger area; Marking and lighting as obstacle; Marking and lighting as UAS; FLARM; Obstacle on charts; Use of transponder; Tactical mitigation through electronic means;
- Ground risk mitigation: Controlled ground area - max. radius around ground station [m]; Designated landing area; Parachute / impact reduction; Others (please describe);
- Site info: Office, hangar, container on site; Grid Connection: I(mport), E(xport); Remuneration exported power;
- Overall permitting: Permit-leading organisation; Other permits, studies: O(rnithological study, (S)ound emission study, B(Imsch); Authorities involved (please list);
- AWE-System: Tether #; Max. size [m2 for projected wing area, m for wing span]; Max tether length [m]; Max. weight [kg]; Max nominal power [kW]; Notes on Permitting; Links to permits (if available); Weblinks.

Data per site (work in progress)

- Latitude
- Longitude
- Name
- Country
- Status
- Start operation
- End operation
- Site operator
- User
- Type
- Description
- Permit to fly: Validity country code
- "In (O)peration, (P)lanned, (V)acant"
- Operation permit type
- Permit issuing authority
- SORA required
- Line of Sight
- NOTAM?
- Permitted altitude [m]
- (P)ilot/op. Required
- (N)ight flight permitted,
- Full (A)utonomy permitted
- Date of 1st flight permit issued (MM/YY)
- Permit validity date (MM/YY)
- Permit extension possible?
- Air risk mitigation: (R)estricted flight zone, (D)anger area
- Marking and lighting as obstacle
- Marking and lighting as UAS
- FLARM
- Obstacle on charts
- Use of transponder
- Tactical mitigation through electronic means
- Ground risk mitigation: Controlled ground area - max. radius around ground station [m]
- Designated landing area
- Parachute / impact reduction
- Others (please describe)
- Site info: Office, hangar, container on site
- Grid Connection: I(mport), E(xport)
- Remuneration exported power
- Overall permitting: Permit-leading organisation
- Other permits, studies: O(rnithological study, (S)ound emission study, B(Imsch)
- Authorities involved (please list)
- AWE-System: Tether #
- Max. size [m2 for projected wing area, m for wing span]
- Max tether length
- Max. weight [kg]
- Max nominal power [kW]
- Notes on Permitting

Figure 12: Test sites in Europe and site-specific data

The map and information are frequently being updated to provide a realistic view of AWE operations world-wide.

3 WP2 Reference models, tools and metrics

3.1 D2.1 Report and Common definitions of metrics and KPIs and gap analysis

3.1.1 Glossary

Task 48 elaborated a glossary which provides a set of commonly used the terms and definitions: https://airbornewindeurope.org/resources/glossary-2/. It contains about 50 terms regarding Power, KPIs, Operational Phases, Trajectories, Wind Speeds, Flight Volumes and Areas and Kites/Aircrafts.

3.1.2 AWE Technology Performance Levels

Furthermore, the NREL methodology of "Technology Performance Levels" (TPLs) by Jochem Weber was discussed extensively and also be applied under WP5. It led to two NREL reports for the US Congress on AWE.

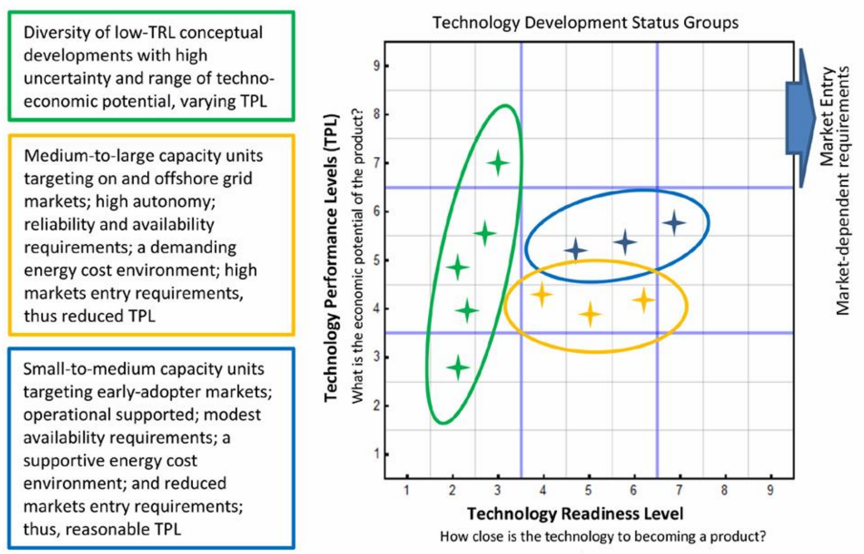


Figure 13: Technology readiness levels (TRLs) and technology performance levels (TPLs) of the main technology development status groups (left) across the global AWE sector. Source: Weber et al. 2021. https://docs.nrel.gov/docs/fy21osti/79992.pdf

3.2 D2.2 Online dissemination platform Reference model(s)

Deliverable D2.2 aims to determine the state of the art of globally available simulation approaches, tools, and platforms.

3.2.1 MegAWES reference model and simulation framework

The MegAWES reference model and simulation framework for a future utility-scale airborne wind energy system (https://github.com/awegroup/MegAWES) is based on the TU Delft graduation project of Dylan Eijkelhof from 2019, co-supervised by DTU and ETH Zurich, building on earlier work of these institutions. The original Matlab/Simulink model included an aeroelastic wing of 42.5 m span, a point mass model to describe the flight dynamics of the tethered aircraft, a discretized tether, and simple controller to fly circular trajectories with a short retraction phase per circle.

Figure 14: Computer rendering of the MegAWES reference model

Integrating the cascaded flight controller developed by Sebastian Rapp, at the time a Marie Skłodowska-Curie PhD fellow at TU Delft, the framework was subsequently adapted for pumping cycle operation, where the aircraft flies multiple figure-of-eight crosswind manoeuvres while reeling out the tether and a relatively short dive towards the ground stations while reeling in the tether. Because of the many operational parameters that affect the power output of pumping cycle operation, the numerical simulation framework was embedded in an optimization framework that aimed at finding the maximum power output given a certain set of constraints (max. tether force, max. altitude, min. reel-in speed, etc.).

In a next step, the aircraft model was upgraded from point mass to rigid body, accounting for translational and rotational degrees of freedom. Two different vertical wind profiles were included, characteristic for onshore and offshore conditions. Numerical simulations using this higher-fidelity model and framework achieved an electrical power output of 3 MW. However, it also became clear that aircraft mass becomes a critical design driver when scaling up to megawatts. The project status was published in Renewable Energy:

The reference model and simulation framework can be used for various purposes. First, it offers, like the NREL 5MW wind turbine, a relatively detailed reference model of a multi-megawatt airborne wind energy system. Second, the framework can be used to test concepts in an early stage of development without the excessive costs of building a real system.

The MegAWES project is by now used by several research groups and development teams around the world:

- BORNE ("Belgium Offshore aiRborne wind Energy", Ghent University and UC Louvain), are using the dynamic simulation and flight control framework to focus on various higher- and lower-fidelity modelling aspects of the kite and the flow field.
- PhD project Filippo Trevisi (Polimi), is improving the aerodynamic model of the aircraft
- Chris Vermillion and team (NC State), is mainly interested in the control framework of Sebastian Rapp, which is part of MegaAWE
- Other users/potential contributors: Nikolaus Vertovek, University of Oxford, and Espen Oland, Kitemill AS.

3.2.2 Soft kite and other simulation models

Examples of TU Delft's work are the simulation models for soft-wing kites [Poland 2023, Poland 2024; Cayon 2023, Thedens], fixed-wing kites [Eijkelhof, Porta Ko] and hybrid kites [Candade, 2023] the Sensor Fusion Technique which is a combination of multiple sensors to overcome individual inaccuracies and limitations and allows prediction of wind and aerodynamic characteristics and the state of the kite at the same time.

A notable contribution to the understanding of wake effects of AWES was published by Polimi: "Refining the airborne wind energy system power equations with a vortex wake model" [Trevisi 2023].

3.2.3 Fechner Julia Kite Power tools

The WP members discussed different reference models. One was presented by Uwe Fechner from ABB in Delft, called Julia Kite Power Tools. It provides a set of packages for fast, dynamic kite power system simulation:

- KiteUtils
- KitePodModels, KiteModels
- WinchModels, AtmosphericModels
- KiteControllers, KiteViewers

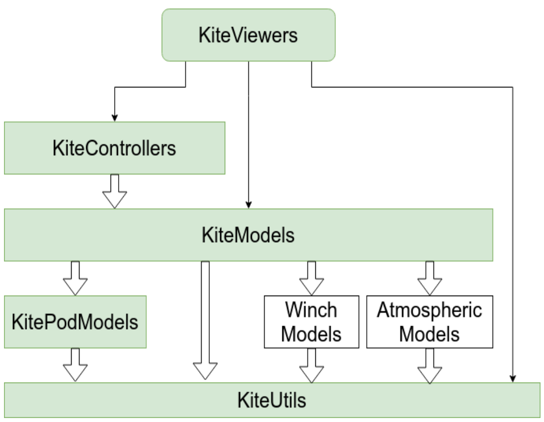


Figure 15: Julia Kite Power Tools. Source: ABB Delft / Uwe Fechner.

Continuous integration is used for quality insurance. Packages can be extended by implementing abstract types. The software can be downloaded as individual repositories in open source from https://github.com/ufechner7.

3.2.4 Impact of wind profiles on ground-generation AWES performance

The study by Sommerfeld et al (2023) investigated the performance of pumping-mode ground-generation airborne wind energy systems (AWESs) by determining cyclical, feasible, power-optimal flight trajectories based on realistic vertical wind velocity profiles. These 10 min profiles, derived from mesoscale weather simulations at an offshore and an onshore site in Europe, are incorporated into an optimal control model that maximizes average cycle power by optimizing the trajectory.

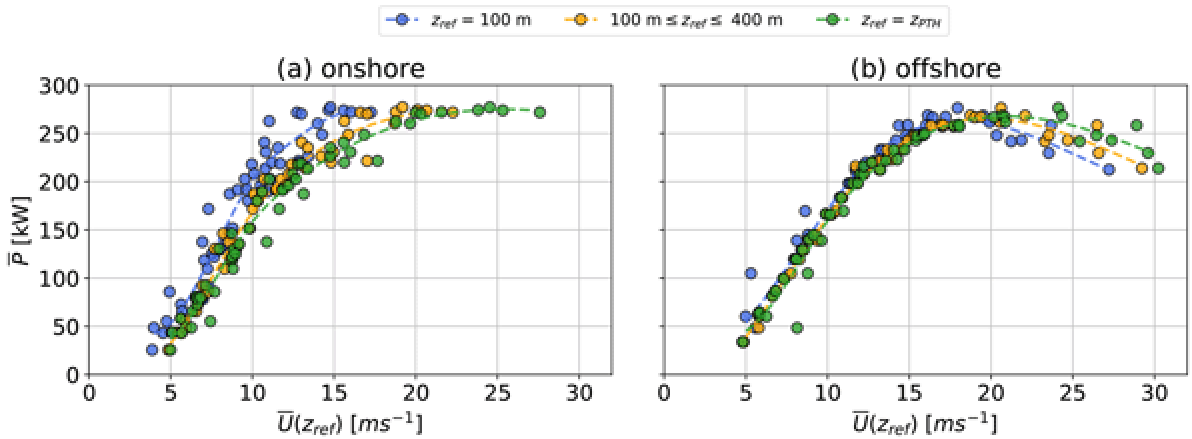


Figure 16: Onshore and offshore power curve approxiamations. Source: Sommerfeld et al. 2023.

The results show that optimal operating heights are generally below 400 m with most AWESs operating at around 200 m.

3.2.5 Validated power curve

With the first externally validated Power Curve presented by SkySails Power in March 2024, the validity of simulations and the real power output could be verified:

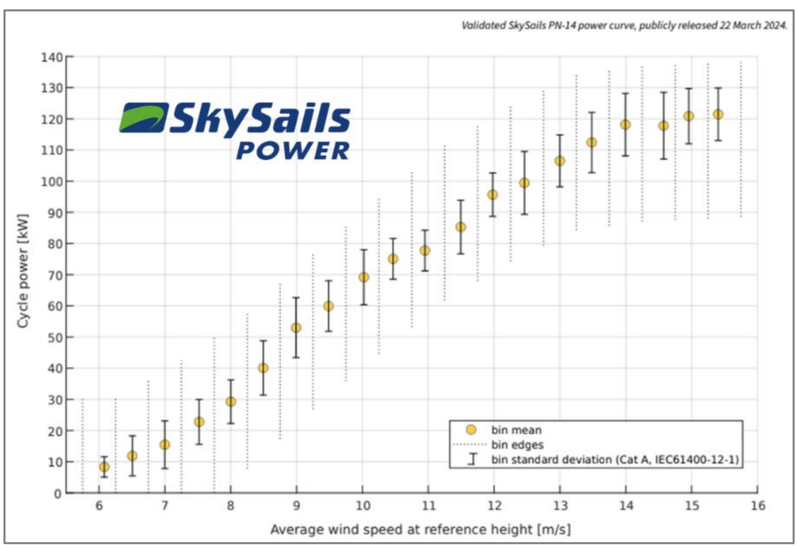


Figure 17: Validated power curve. Source. SkySails Power 2024

This is considered a major milestone for the AWE sector – together with the recognition of AWE in the German Renewable Energy Act (EEG) in April 2024. The ground-breaking work by SkySails is now being used in the elaboration of the first AWE-specific standard IEC 61400-12-80 on power performance measurement und IEC TC 88.

3.3 D2.3 Centralized design tool database

This deliverable aims to determine the state of the art of globally available simulation approaches, tools, and platforms.

3.3.1 Reference Economic Model

This work TU Delft and Polimi is the result of a collaborative effort between industry and academia. The technical report and the developed computer code provide parametric cost models that aim to estimate both capital expenditure (CapEx) and operational expenditure (OpEx) associated with each component of airborne wind energy systems (AWESs). Furthermore, the report identifies relevant design metrics that could be used as objectives for the optimisation and refinement of AWES designs. These metrics will not only aid in evaluating the performance and efficiency of AWESs but will also guide future research and development efforts.

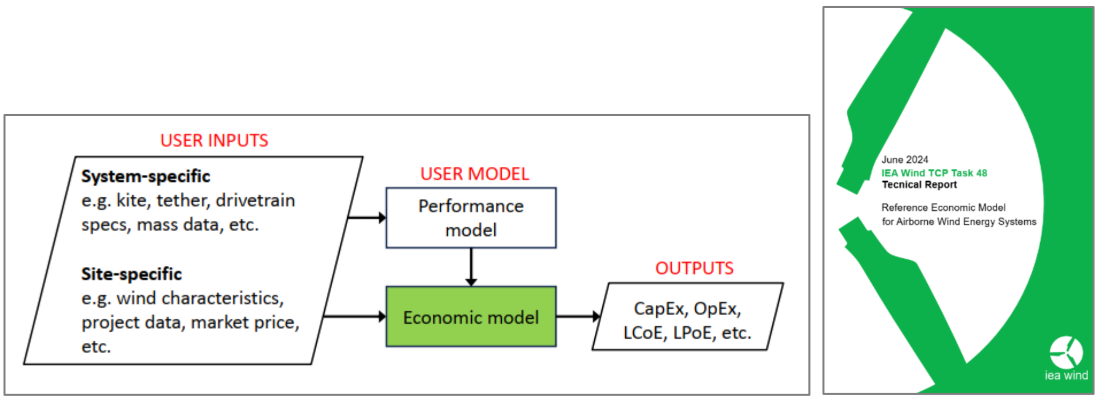


Figure 18: Flowchart representing the inputs and outputs of the developed economic model. Source: Joshi 2024

In addition to cost modelling and design metrics, the report delves into potential markets where AWESs could play a significant role in the global energy supply mix. This report aims to be a valuable resource for researchers, industry and policy makers who want to understand the economic aspects, design considerations and market potential of AWESs. It sets the groundwork for informed decision making, road mapping of technology development, and collaborative efforts to advance the adoption and deployment of AWESs on a global scale.

3.3.2 Other works on design tools

Various academic works were carried out, e.g. on Safety-Aware Hybrid Control of AWE systems [Vertovec 2024], the study on Power Smoothing by Tether Force Control for Megawatt-Scale AWE systems [Hummel 2024], or the study on optimal wing design to maximise power [Trevisi 2024], see Figure 19.

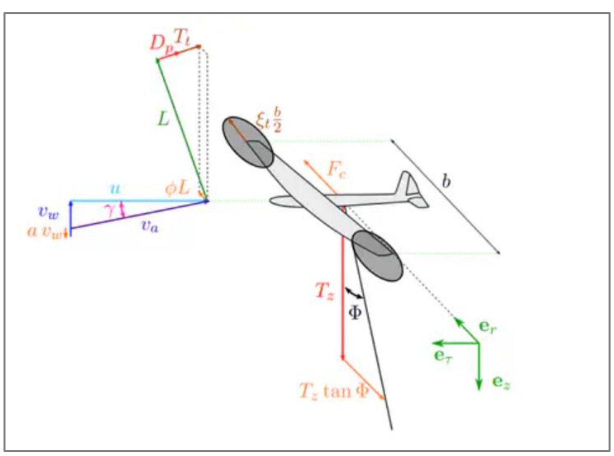


Figure 19: Optimal design of windplanes. Source: Trevisi 2024

The following publications which contain work on design tools and models from various institutions were issued (see also references at the end of this report):

- *Poland et al: Modelling Aero-Structural Deformation of Flexible Membrane Kites (TUD)*
- *Cayon et al: Fast Aero-Structural Model of a Leading-Edge Inflatable Kite (TUD & DTU)*
- *Thedens et al: An Aero-Structural Model for Ram-Air Kite Simulations (Skysails & TUD)*
- *Porta Ko et al: Optimisation of a Multi-Element Airfoil for a Fixed-Wing Airborne Wind Energy System (Kitemill & TUD)*
- *Eijkelhof et al: Low- and High-Fidelity Aerodynamic Simulations of Box Wing Kites for Airborne Wind Energy Applications (TUD)*
- *Schutter et al: AWEbox: An Optimal Control Framework for Single- and Multi-Aircraft Airborne Wind Energy Systems (UFreiburg) -> could also be in WP5*
- *Pynaert et al: Wing Deformation of an Airborne Wind Energy System in Crosswind Flight Using High-Fidelity Fluid–Structure Interaction (UGhent)*
- *Viré et al: Effect of Chordwise Struts and Misaligned Flow on the Aerodynamic Performance of a Leading-Edge Inflatable Wing (TUD)*
- *Fernandes et al: L0 and L1 Guidance and Path-Following Control for Airborne Wind Energy Systems (UPorto)*
- *Arshad Uppal et al: Cascade Control of the Ground Station Module of an Airborne Wind Energy System (UPorto)*
- *Castro-Fernandez et al: Three-Dimensional Unsteady Aerodynamic Analysis of a Rigid-Framed Delta Kite Applied to Airborne Wind Energy (UC3M)*
- *Trevisi et al: Flight Stability of Rigid Wing Airborne Wind Energy Systems (Polimi)*

3.4 D2.4 Validation of simulations and upscaling assumptions

3.4.1 Reference kite V3

TU Delft uses the V3 kite for comparing simulations and test flights. Results of ongoing studies are published on https://awegroup.github.io/TUDELFT_V3_KITE/ and shared within Task 48.

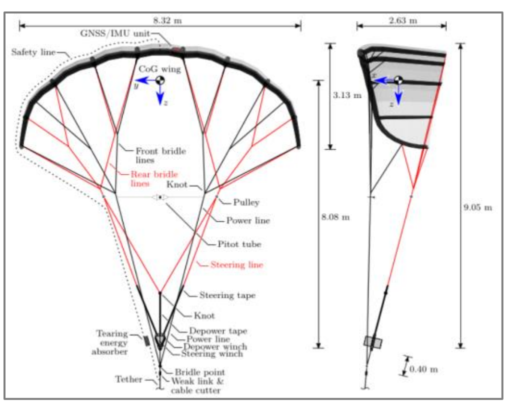


Figure 20: TUD V3 kite. Source: TUD.

Other universities apply similar methods, using small test kites to gather data from test flights, e.g. UC3M.

3.4.2 Swinging motion of a kite with suspended control unit flying turning manoeuvres

The flexible-membrane kite employed by some airborne wind energy systems uses a suspended control unit, which experiences a characteristic swinging motion relative to the top of the kite during sharp turning manoeuvres. This paper assesses the accuracy of a two-point kite model in resolving this swinging motion using two different approaches: approximating the motion as a transition through steady-rotation states and solving the motion dynamically. The data used were using a 25 m^2 V3.25B kite of Kitepower.

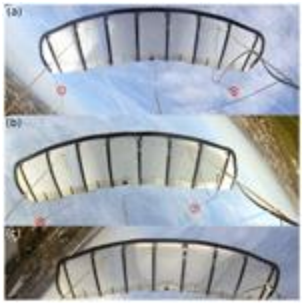


Figure 21: Swinging motion of a kite with suspended control unit. Source: Schelbergen et al. 2024.

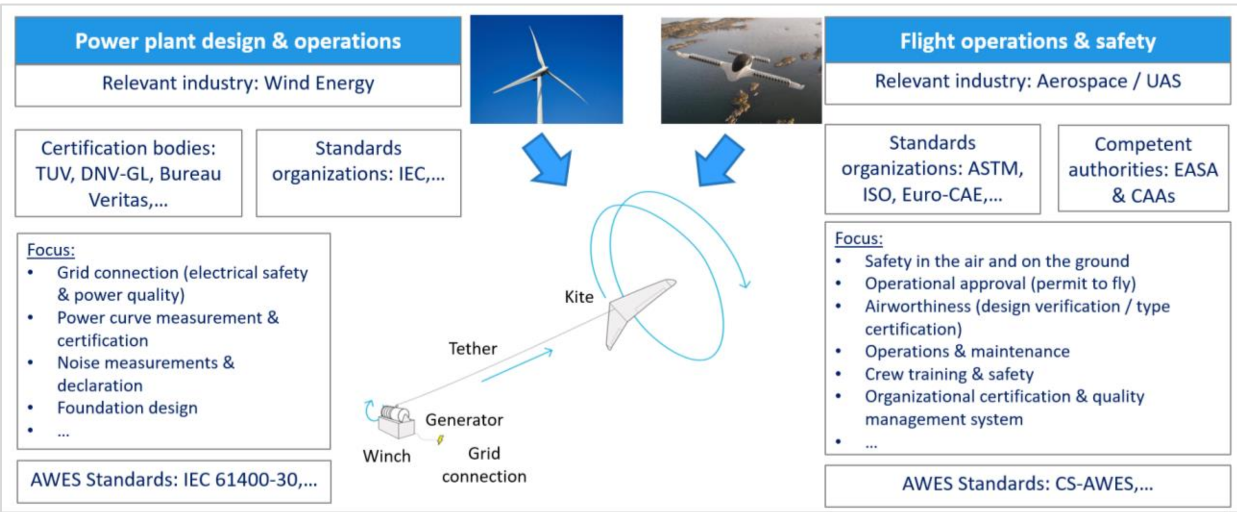
The study shows that the inertia of the suspended control unit has a large effect on the roll of a flexible kite during turns in the reel-out phase. During the reel-in phase, the pitch of the kite changes due to the weight and drag of the control unit and increased tether sag. These effects are not resolved when the kite is modelled with a single point mass. With two point masses, one at the wing and one at the control unit, the steady-rotation-state model performs reasonably well in capturing the pitch and roll with little extra computational effort. A two-point model of the kite can thus be a powerful tool for the performance modelling of flexible kite systems.

4 WP3 Safety and regulation

4.1 D3.1 Whitepaper on AWES safety

In April 2023, the first version of the White Paper on “Safe Operation and Airspace Integration of Airborne Wind Energy Systems” was published. It outlines the needs and requirements of the Airborne Wind Energy (AWE) industry with regards to safe operation and airspace integration of AWE Systems and lays out a number of recommendations related to policies and regulation.

The paper addresses policy makers and regulators from both the energy and the aviation sector, including ministries of energy, ministries of transport/aviation, national and regional civil aviation authorities, EASA, and the European Commission. Its intention is to provide the context and framework of how the AWE sector plans to secure safe operation and airspace integration. Hence, while the recommendations are mainly directed to authorities dealing with airspace related permitting, it will also help authorities that are in charge of energy-related installations to understand the specific requirements for “flying wind energy systems”.

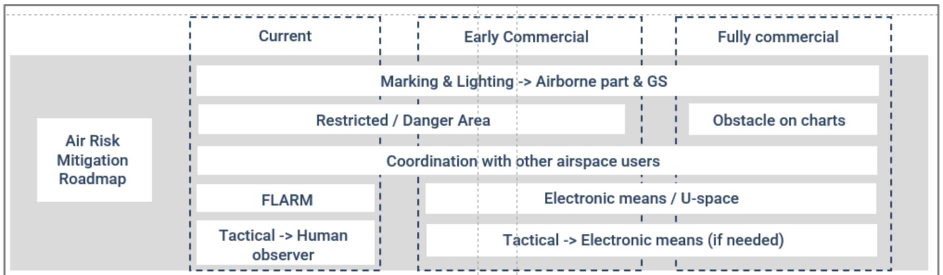


This paper aims to trigger – and where possible contribute to – the development of international standards and guidelines for AWE. It does not intend to provide specific guidance for a particular system at a particular site, instead it is providing general guidelines for the AWE sector. The final goal is to ensure that AWE systems can and will be operated in a safe and economically viable way so that the AWE sector can contribute to reaching the renewable energy and climate targets. The paper was also translated to German in order to inform specifically German policy makers.

The findings of the previous White Paper were applied and further elaborated in various permitting process and cross-border applications. The discussions within Task 48 on airspace integration have been the basis for detailed regulatory proposals for the German context. It is planned to extend the lessons learned to other jurisdictions in order to speed up the permitting processes for AWE systems.

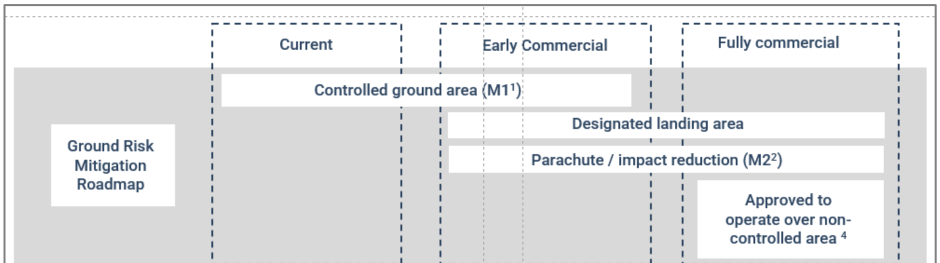
4.2 D3.2 Concept of operations (CONOPS) and SORA guidelines

Within this deliverable, ground-breaking work was conducted by Corey Houle (TwingTec) expanding on the the CONOPs and SORA (Specific Operation Risk Assessment; developed for unmanned aircraft systesm) approach. It includes the results of a survey conducted with ten leading AWE developers on air risk and ground risk mitigation measures and proposes recommendations for further developing safety measures for the AWE sector:



Air Risk Mitigations[1]	Current	Early commercial	Fully commercial
M&L -> Airborne part & GS	50%	91%	91%
Restricted / danger area	36%	64%	27%
Obstacle on charts	0%	45%	73%
Coordination	36%	55%	36%
Electronic means / Uspace	18%	95%	91%
Tactical mitigations	91%	55%	36%

Figure 22: Survey: Air risk mitigation measures. Source: Houle 2023



Ground Risk Mitigations[3]	Current Operations	Early Commercial	Fully Commercial
Controlled Ground Area	50%	55%	41%
Designated landing area	18%	45%	55%
Parachute / impact reduction	27%	36%	45%
Approved to operate over non-controlled areas	18% [5]	18%	64%

Figure 23: Survey: Ground risk mitigation measures. Source: Houle 2023

Furthermore, it provides clear guidelines on how to apply the SORA methodology for AWE systems.

Another paper on “Operation Approval for Commercial Airborne Wind Energy Systems” was published by TUD (Salma et al. 2023). It assumes that that the European Union Aviation Safety Agency will approve commercial systems as unmanned aircraft systems within the “specific” category, requiring risk-based operational authorization

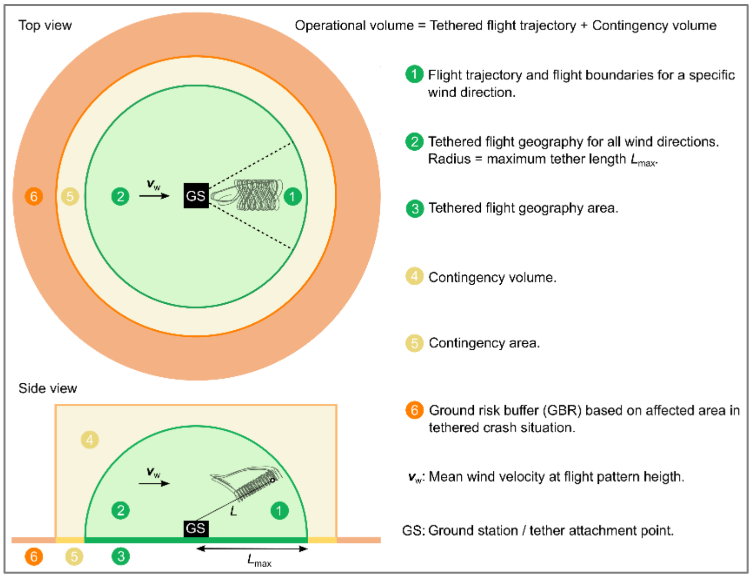


Figure 24: Definition of the operational volume for AWES and related terminology. Source: Salma et al. 2023.

In this paper, the risk assessment methodology for AWE systems is interperted by going through the ten required steps of the recommended procedure for a commercial flexible-wing AWE system. It finds that the air risk mitigations improve the consolidated specific assurance and integrity level by a factor of two. It is expected that the framework will increase the safety level of commercial airborne wind energy systems and ultimately lead to operation approval.

4.3 D. 3.3 U-Space integration concept

The topic of U-Space was discussed in the first meetings of Task 48 WP3. Especially experts from Swiss FOCA provided insights into the concept and its potential application for the AWE sector. However, due to lack of funding and no immediate use case for AWE companies, it was not possible to carry out further activities on this matter. It may become of interest again in the course of the 2nd term of Task 48.

4.4 D3.4 Overview of design concepts for safe automatic operation

The development of AWE-specific standards as part of IEC-61400 has been started. The approach of an overarching new series IEC-61400-80 on AWE systems – using the -2 standard on small wind sytems as baseis – as well as an AWE-specific on power performance measurements (IEC 61400-12-80) have been accepted by the TC 88 after having successfully past the vote of the national committees. The working group consists of experts of currently 5 countries.

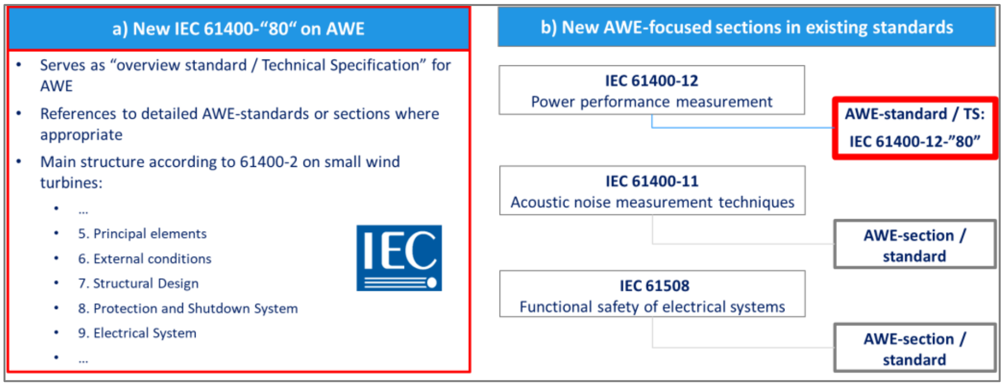


Figure 25: First two AWE-specific IEC 61400 standards

Furthermore, two studies looked into Standardisation and Certification of Airborne Wind Energy [Kinsley 2024] and a Standardization Roadmap [Fagan 2024].

5 WP4 Social Acceptance and environmental impacts

5.1 D4. LCA for AWE

Based on a Master Thesis at TU Delft and elaborated under the MegaAWE project, a paper on the Life Cycle Analysis of a fixed-wing AWE system was finalized. The results showed that under this specific configuration, this AWE type could save up to 70% of the material and reduce the GHG potential by about 40%. The figures were confirmed by preliminary data from a SPI study in Switzerland, presented at the AWEC in Milan.

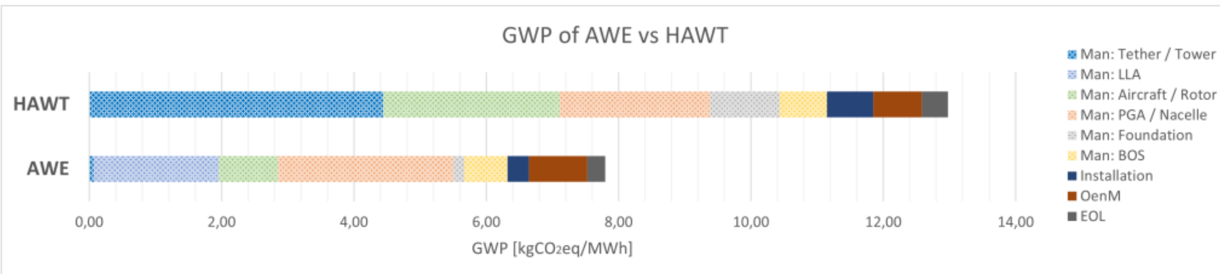


Figure 26: LCA Analysis: Global Warming Potential of an AWE system compared to a Horizontal Axis Wind Turbine (HAWT) system

After the Life Cycle Analysis carried out under the MegaAWE project, a number of new LCA studies have been initiated. The following table gives an overview of the current status:

Table 3: LCA studies on AWE

Name(s)/Position	Affiliation	Study goal	Project type	Company(ies) involved	Technology
Yara Hugo	TU Berlin (tbc)	Overall optimisation	Bachelor thesis	Enerkite	Semi-rigid ground gen
Adrien Guilloré, Samuel Kainz (Research assistants, PhD candidates) Irène Morlando (past M.Sc. student who finished her thesis on this) Jo Gessert (current M.Sc. student on this topic)	TU Munich	1) Sizing of kite components and upscaling 2) Automatized LCA model to be included in the Design phase On the level of single system, not yet farm (will come later) Structural sizing: Selecting size of the kite for optimal GWP. Starting from existing optimisation model (Matlab) Design perspective: Not only optimising costs, but also GWP Scaling laws: Masses, components Design variables, not one fixed technology Master thesis set up LCA: Kitekraft 5 kW. Already some scaling	Master thesis, Semester thesis	Kitekraft	Rigid kite Fixed wing fly-gen system

Name(s)/Position	Affiliation	Study goal	Project type	Company(ies) involved	Technology
		100kW-500kW (--> Benefits of scaling on LCIA scores?)			
Samuel Eiriz	PSI/ETH	1) Guidelines for LCA in AWE sector 2) LCA of soft wing AWE. General focus; goal is to have a first LCA of soft wing AWE with some (aggregated) results which can be used by Airborne Wind Europe. LCI of Kitepower and Skysails system, but confidential. Tbd what will be shared in the final report to the public.	Bachelor Thesis	Kitepower, Skysails	Soft-wing ground gen
Karin Treyer	PSI	LCA of TwingTec AWE	Project	TwingTec	Fixed-wing fly-gen
Matteo Alghiri (current M.Sc student), Gaia Brussa (Research Assistant), Mario Grosso (Professor)	Politecnico di Milano	LCA of soft wing AWE (company/ies to be confirmed). Focus on critical raw materials and material demand with respect to conventional wind turbines (if sufficient data are retrieven from AWE side)	Master thesis		soft wing

These LCAs have found that AWE has low impacts on climate change with results around 10 g CO2-eq/kWh and a low material intensity of ca. 1-3 kg/MWh, with no or little use of Critical Raw Materials. It has been also found that LCA of AWE need to adopt a prospective view for scaling up and future applications: When deployment of off-grid or wind park AWE systems will take speed in the coming decades, both technical design and supply chains or the energy system will have changed.

Prospective LCA tries to include learning curves, scaling rates, and changes in the background into the study model. Prospective LCA is not yet a specific established LCA methodology, therfore LCA practitioners have to make various decisions on future scenarios.

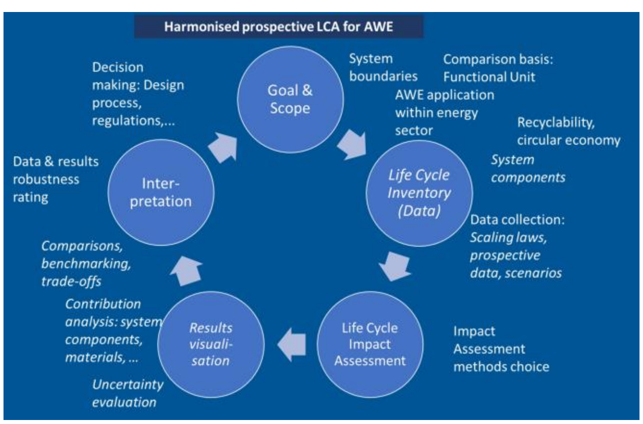


Figure 27: Propsective LCA. Source: Treyer 2024.

5.2 D4.2 Repository of surveys/studies on social acceptance & impacts on birds/bats

In order to increase the field's understanding of the acceptance of AWE and thereby facilitate development and deployment, empirical social science research have been carried out by Helena Schmidt (TU Delft) in collaboration with the health and environmental psychology group at MSH Medical School Hamburg (directed by Prof. Dr. Gundula Hübner, Task 28).

5.2.1 Literature review

A literature review carried out by Helena Schmidt from TU Delft assessed the current state of knowledge on the social acceptance of AWE. A systematic literature search led to the identification of 40 relevant publications that were reviewed. The reviewed literature viewed the social acceptance of AWE optimistically but lacked scientific evidence to back up its claims. It seemed to overlook the fact that the impact of AWE's characteristics (e.g., visibility) on people's responses will also depend on a range of situational and psychological factors (e.g., the planning process, the community's trust in project developers). The review concluded that future research is needed that empirically assesses how people perceive and respond to AWE. (Schmidt et al. 2022).

5.2.1 Survey and interviews of residents

In June 2022, an interview-based survey study was conducted among residents living around SkySails Power's AWE test site in Northern Germany. It aimed to explore how residents perceive energy-producing kites by comparing the community acceptance of an airborne wind energy system and a wind farm in Germany. A total of 55 residents living up to 2.5 km from the site were recruited through letters, calls, leaflets in mailboxes, a newspaper article, posters, Facebook posts, and announcements by local organizations. Structured, in-person interviews took place in the participants' homes. The journal manuscript discussing the results of the study is currently in preparation.

This first community acceptance study of an AWES [Schmidt et al. 2024] indicates that residents rate the visual impacts of a nearby AWES better than those of a wind farm. In contrast, noise, ecological, and safety impacts were rated similarly. The study further shows that many research findings from established renewables apply to this emerging technology. Specifically, impacts on nature and residents are related to lower acceptance, and residents' experience of the project implementation is linked to their evaluations of a local AWE project.

5.2.2 Exploring Noise Annoyance and Sound Quality for AWE systems: A Listening Experiment

A study on noise annoyance and sound quality for AWE systems [Schmidt et al. 2025] identified sharpness as a key predictor of noise annoyance for AWESs, with fixed-wing kites eliciting higher annoyance than soft-wing designs. Fixed-wing kites had sharper and more tonal sound profiles, while the soft-wing kite had higher loudness values. Participant characteristics influenced the impact of loudness and tonality on annoyance, highlighting the complexity of subjective noise perception. The findings further emphasize the limitations of conventional noise metrics in assessing AWES noise, suggesting the need for tailored acoustic models.

5.2.3 GrowFlowFly

Another project was successfully developed jointly among Task 48 and Task 28 members which will be funded by the German ministry of economy and climate (BMWK): **GrowFlowFly.** It discusses social acceptance issues of the three technologies AWE, Floating and Agri-PV. Among others, it allowed computer-based visualisation of these novel technologies in a given region. Partners were the University Martin-Luther-University Halle-Wittenberg (MLU), TUM, RWTH Aachen.

5.2.4 *Repository of environmental impact studies*

Over the course of the 1st term of Task 48, Airborne Wind Europe has gathered and published available studies on environmental impacts from various AWE projects on its website https://airbornewindeurope.org/social-acceptance-2

The findings have been summarised in the Energy Read, see below. As a high uncertainty remains, more studies, data and information from AWE projects are required.

5.3 D4.3 Guidelines for site selection and environmental impact mitigation measures

The EU Horizon Project **JustWind4All** included a Living Lab on social acceptance of AWE systems, with a with a particular focus on participation, energy justice and social innovation (AWEurope is project partner) in the region of Brandenburg (Germany) where Enerkite develops a new location. Various workshops have been carried out with a wide range of stakeholders.

Figure 28: JustWind4All Energy Read. Source: Airborne Wind Europe 2025.

The "Energy Read" is structured in two main section:

a) A state of the art overview of crucial topics relevant for AWE technology developers such as safety, visual impacts, sound emissions, ecological effects, attitudes and perceptions and site location. For each of these topics concrete recommendations are given.
b) A focus on the different stages of project development thus providing mainly recommendations for AWE project developers.

The key recommendations are summarized below:

GUIDELINES

TREAT COMMUNITY ENGAGEMENT LIKE PERMITTING OR ENGINEERING—IT'S A CORE PROJECT DISCIPLINE
Budget for staff time, events, consultants, and communications, even if this may be challenging for AWE companies.

ENGAGE EARLY WITH COMMUNITIES
Initiate communication during the feasibility and site selection phase – before securing permits. Early outreach builds trust and gives developers insight into local concerns before decisions are finalised.

ENSURE TRANSPARENCY THROUGHOUT THE PROJECT
Provide clear, honest information about safety, environmental impact, timelines, and system limitations. Transparency is critical - especially for a new technology like Airborne Wind Energy where public knowledge is still developing.

ADAPT ENGAGEMENT TO THE LOCAL CONTEXT
Tailor outreach to reflect local identity, land use values, and concerns. Explain the potential advantages of AWE, such as lower noise, minimal visual impact, and a small land footprint, in terms that resonate locally.

OFFER LOCAL BENEFITS
Consider options such as job creation, community investment, or educational partnerships. Demonstrating clear local value can significantly increase acceptance. However, do not overpromise or exaggerate local benefits.

MAINTAIN ONGOING COMMUNICATION AND RESPONSIVENESS
Keep communities informed during construction and operation. Address emerging issues quickly and maintain open, two-way communication channels.

Figure 29: JustWind4All Energy Read: Summary of guidelines. Source: Airborne Wind Europe 2025.

5.4 D4.4 Circular economy / cradle-to-cradle aspects for AWE, incl. design process

Given that there was no budget for this deliverable, only preliminary discussions started on how to apply a circular economy approach to AWE systems.

These included talks with Julie Teuwen (TUD). Preliminary results from performance simulations show that the use of biodegradable components (e.g. using hemp instead of carbon fibre) would not be realistic at this stage given the high loads that fixed wing systems will have to endure.

6 WP5 AWES Architectures

6.1 D5.1 Design space representation

WP5 developed an overview of the design space which considers the various different concept of AWE systems, see figure below.

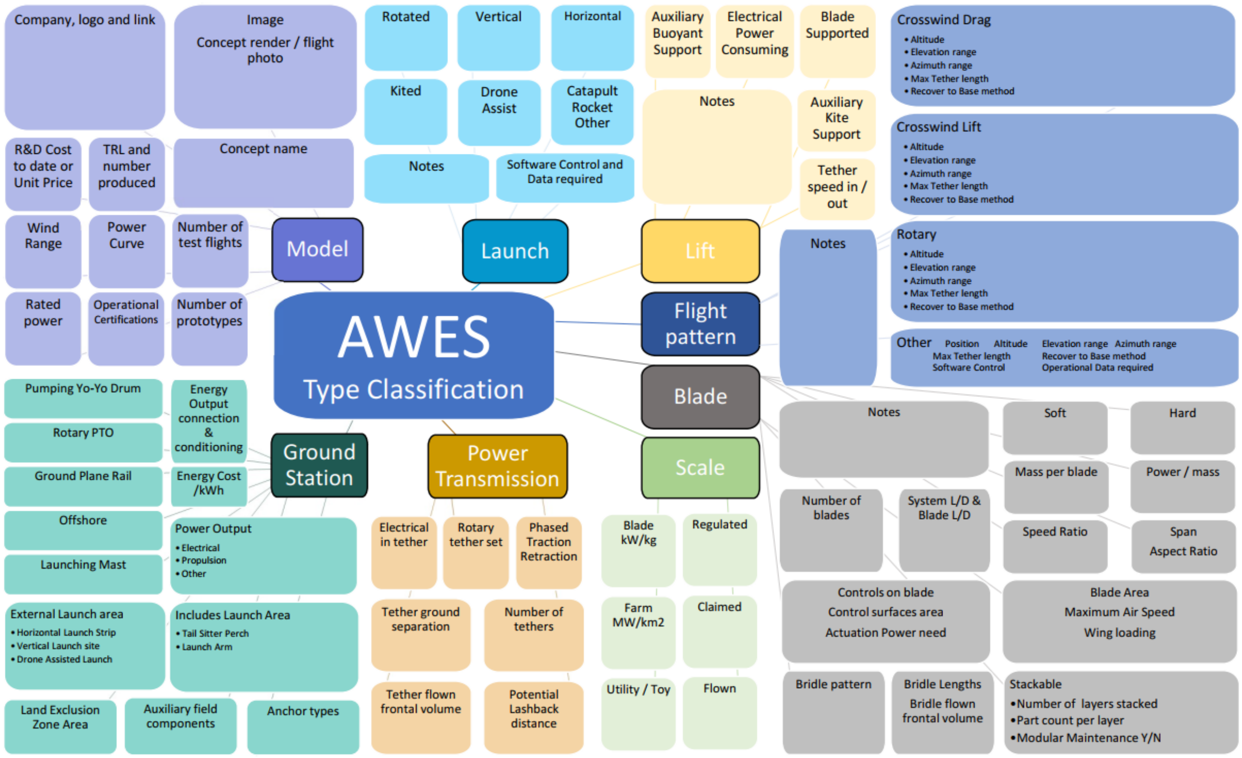


Figure 30: AWES Type Classification / Design Space

To investigate less prominent AWE architectures, WP5 worked closely with University of Freiburg, namely on "Vertical Airborne Wind Energy Farms with High Power Density per Ground Area based on Multi-Aircraft Systems" (De Schutter et al 2023) and "An Optimal Control Framework for Single- and Multi-Aircraft Airborne Wind Energy Systems" (De Schutter et al 2023).

6.2 D5.2 Application / market specific recommendations / Performance Criteria

The focus of the WP5 team with regards to applying the AWE architectures and providing recommendations for AWES deployment has been on the definition of Performance Assessment criteria. These can be used to perform a trade-off analysis between implementation options in the Airborne Wind Energy design space. The criteria include:

- Efficiency
- Reliability
- Availability
- Complexity
- Automatability
- Scalability
- Airborne Mass
- Durability
- Ductility
- Safety
- Potential
- Cost
- Investability
- Social Acceptability

6.3 D5.3 Oversight on AWES R&D state, trends and needs

6.3.1 BVG White Paper

In 2022, the AWE sector commissioned a study to to provide independent insight into the market potential of AWE technologies, AWE cost trends, and capture the energy market challenges.

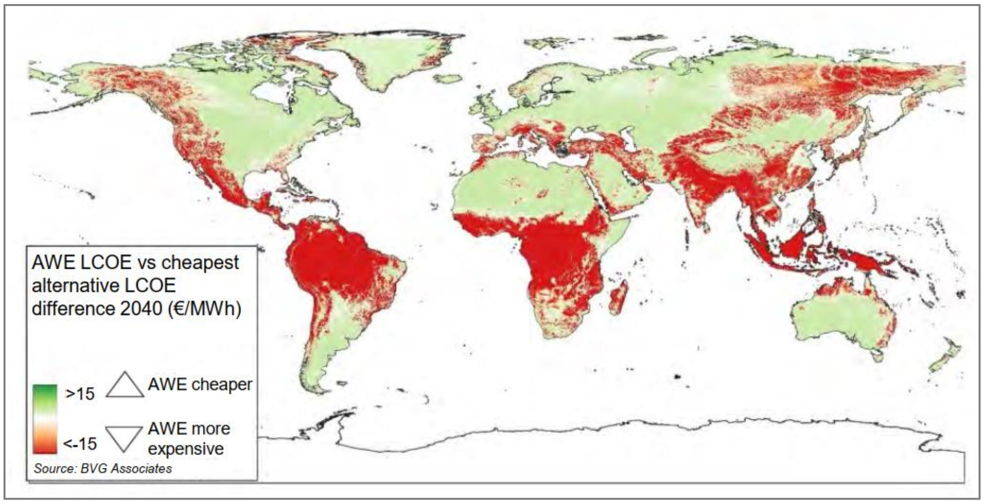


Figure 31: Global LCOE for representative AWE system versus cheapest alternative in 2040 for 500kW project. Source: BVG 2022.

It found that 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.

6.3.2 Autonomous Airborne Wind Energy systems: accomplishments and challenges

This paper by Fagiano et al. (2022) describes the state-of-the-art of AWE technology with a system perspective and a critical view on some fundamental aspects, presents latest automatic control results by prominent industrial players, and finally points out the most important challenges on the road to fully autonomous AWE systems.

6.4 D5.4 Definition of a portal for identifying AWES development potential

This deliverable "Definition and specification of a portal for identifying AWES engagement and development potential" had to be abandoned as none of the participants could secure budget for the implementation and operation of such a portal.

7 Cooperation with other IEA Tasks

Task 48 has cooperated with the following tasks by inviting experts to WP meetings and vice-versa. While with some Tasks collaboration with close, with others only occasionally information exchange took place. It is planned to increase the exchange with other tasks in future.

- Task 44 – Flow Farm Control coordinates international research in the fields of wind farm flow control.
- Task 51 – Forecasting for the weather driven Energy System focuses on improving the value of renewable energy forecasts. In the context of the Meriodional project and other overlaps regarding wind resources, members of both tasks participated in the other tasks meetings at several occasions.
- Task 52 – Large-Scale Deployment of Wind Lidar supports international collaboration on wind lidar related topics and applications.
- Task 57 – JAM – Joint Assessment of Models fosters communication, coordination and collaboration among worldwide experts and stakeholders.
- Task 43 – Wind Energy Digitalization aims to help bring about a revolution in the way technology is used in the wind energy industry.
- Task 41 – Enabling Wind to Contribute to a Distributed Energy Future coordinates international research on distributed wind turbine technology, technology development, or assessment to allow distributed wind to integrate into future markets, and processes or procedures to support the cost-effective development of distributed wind technologies.
- Task 50 – Hybrid Power Plants coordinates international research and development in the field of hybrid wind power plants.
- Task 55 – REFWIND – Reference Wind Turbines and Plants coordinates international efforts to rigorously define reference wind turbines and plants.
- Task 42 – Wind Turbine Lifetime Extension focuses on wind turbine lifetime extension and coordinates international research activities towards the assessment of the remaining operational life of wind turbines near the end of their certified design life and identification of strategies for extending the end of useful life.
- Task 59 – The Wind Energy-Environmental Research & Engagement Network (WREN) is the leading international forum for facilitating the deployment of wind energy technology around the globe through a better understanding of environmental issues and demonstrated solutions for wildlife challenges.
- Task 60 – CYCLEWIND – Harmonised Life Cycle Assessment for Wind Power focuses on the environmental sustainability assessment of wind power from a life cycle perspective.
- Task 53 – Wind Energy Economics evaluates cost and value primarily in the context of anticipated deep decarbonization developments and emerging wind energy applications.
- Task 28 / 62 – Social Science for Collaborative Wind Energy Planning & Participation. The closest links were established with this task thanks to the close collaboration between Gundula Hübner and Helena Schmidt. John Aston gave also various important ideas for the Energy Read.

8 Conclusions and recommendations

8.1 Conclusions

8.1.1 Achievements of Task 48

Task 48 has been a crucial and very valuable platform for the AWE sector. Successes are for instance:

- IEA Wind TCP Task 48 has been established as ***the*** platform for international exchange of AWE stakeholders
- Diverse collaborations, also towards funded EU and national research projects (Horizon/ Interreg etc.) have been developed under this umbrella
    - Horizon MERIODIONAL (WP1/2)
    - Horizon Europe: JustWind4All (WP4)
    - Horizon Europe: AWETRAIN (WP1/2/3/4)
    - Interreg NWE: MegaAWE and DEM-AWE (WP1/2/3/4)
- Over 50 scientific papers per year were published through or with support of Task 48
- Regular Work Package meetings (> 40 online/ in-person) allowed for presenting latest research & development results of universities and companies as well as for inviting new stakeholders to evaluate potential collaboration, given the open exchange
- The WP3 Whitepaper "Safe Operation and Airspace Integration of AWE Systems" acts now as basis for implementing AWE in a regulatory frameworks worldwide
- Task 48 meetings were held at the WESC 2022 in Glasgow and WESC 2024 and Nantes, as well as back-to-back to the AWEC 2019 in Glasgow, AWEC 2022 in Milan and AWEC 2024 in Madrid.

8.1.2 Status of the Airborne wind energy (AWE) sector and the need for Task 48

The value proposition of Airborne wind energy (AWE) remains valid: AWE has the potential to give access to stronger and more stable high-altitude wind resources, including in remote areas and floating offshore, and thus play an important part in the future energy mix. It also reduces material consumption which leads – in combination with a higher capacity factor – to potentially very low LCOEs and lower carbon and environmental impacts. Furthermore, it may be modified to provide propulsion and power for the maritime shipping sector.

The AWE sector is moving towards commercialization, the outputs of Task 48 will have to focus even more tangible benefits for the industry, i.e. going beyond research studies and bringing theoretical findings into practise. There are currently over 60 organisations working on AWE, thereof about a dozen technology developers and the others being academia, research institutions and suppliers. The strong industrial participation is a key success of Task 48, and the supporting research in universities supports the education and training of potential future employees.

Many topics addressed by Task 48 over the first term continue to be relevant, new ones are coming up: There are still many challenges to be solved or investigated concerning AWE safety standards and technical guidelines, resource and deployment potentials, markets, engineering issues, environmental impacts and social acceptance, regulatory as well as financial and policy challenges. Moreover, the imminent industrialisation of the AWE sector requires a new focus on manufacturing and mass production.

8.2 Recommendations and future work

Given the above, there is the continued need for unbiased, independent, high-quality information for industry, academia and policy makers which the Task 48 can deliver.

The 2nd term of Task 48 will work on the following Work Packages.

WP1: Materials, Manufact. & Supply	WP2: Models and tools	WP3: Regulation and deployment	WP4: Social Acceptance
• Design for Circularity • Materials • Manufacturing • Scaling • Supply Chain • Life-Cycle Analysis • Cost efficiency • Economies of scale	• Joint reference models • Centralized design tools • Simulation vs. test flights comparison • Grid integration simulations	• Deployment potential & markets • Safe Airspace integration • Regulatory frameworks / permitting • Market preparation / harmonisation • Standardization & certification • Hybrid Power Plants	• Stakeholder acceptance (on all levels) • Environmental impacts, e.g. sound, flora/fauna, humans • Awareness raising
• Design guidelines • Manufacturing roadmap • Economic metrics	• AEP prediction toolchain • Centralized design tool database	• Market-entry studies • Airspace integration concepts • AWE standards	• Stakeholder guidelines • Repository surveys & studies (incl. LCAs)

Figure 32: Task 48 Work Programme of 2nd term

For more details see the 2nd term Work Programme.

9 Publications, presentations, dissemination

The reference list shows the significance of Task 48 on delivering scientifically sound results:

Airborne Wind Europe (2021), Life-Cycle Assessment of an Airborne Wind Energy System, Interreg NWE - MegaAWE project. Petrick, K., van Hagen, L., Schmehl, R., Wilhelm, S. https://airbornewindeurope.org/megaawe_airbone-wind-energy-system-life-cycle-analysis_2021-09-29-2/

Airborne Wind Europe (2023), Safe Operation and Airspace Integration of Airborne Wind Energy Systems – White Paper of the AWE industry. Petrick, K., Houle, C. https://airbornewindeurope.org/studies-papers/safe-operation-and-airspace-integration-of-airborne-wind-energy-systems/

Bouman, N. (2023), Aeroacoustics of Airborne Wind Energy Systems. Msc Thesis, Delft University of Technology. https://edu.nl/dq6df

BVG Associates on behalf of Airborne Wind Europe, "Getting airborne – the need to realise the benefits of airborne wind energy for net zero", September 2022, https://airbornewindeurope.org/white-paper-for-the-airborne-wind-energy-sector-by-bvg-associates-commissioned-by-airborne-wind-europe/

Candade, A. (2023), Aero-structural Design and Optimisation of Tethered Composite Wings: Computational Methods for Initial Design of Airborne Wind Energy Systems. Ph.D. Thesis, Delft University of Technology, Delft. https://doi.org/10.4233/uuid:c706c198-d186-4297-8b03-32c80be1c6df

Cayon, O., Gaunaa, M. and Schmehl, R.: Fast Aero-Structural Model of a Leading-Edge Inflatable Kite, Energies, 16(7):3061, 2023. https://doi.org/10.3390/en16073061

Cayon, O., Gaunaa, M., Schmehl, R. (2023), Fast Aeroelastic Model of a Leading-Edge Inflatable Kite. Energies 16(7), 3061. https://doi.org/10.3390/en16073061

Coca-Tarrago (2023), Site Identification Analysis for AWE Devices. A case study in Germany. Deliverable Report. https://doi.org/10.5281/zenodo.10462306

De Schutter, J. Harzer, M. Diehl (2023), Vertical Airborne Wind Energy Farms with High Power Density per Ground Area based on Multi-Aircraft Systems. European Journal of Control, 74, 100867. https://doi.org/10.1016/j.ejcon.2023.100867

De Schutter, R. Leuthold, T. Bronnenmeyer, E. Malz, S Gros, M. Diehl (2023), AWEbox: An Optimal Control Framework for Single- and Multi-Aircraft Airborne Wind Energy Systems. Energies, 16(4), 1900. https://doi.org/10.3390/en16041900

Edward Fagan (2024). Airborne Wind Energy Certification Roadmap. https://zenodo.org/records/14219245

Eijkelhof, D., Buendía, G., Schmehl, R. (2023), Low- and High-Fidelity Aerodynamic Simulations of Box Wing Kites for Airborne Wind Energy Applications. Energies 16(7), 3008 (2023). https://doi.org/10.3390/en16073008

Eijkelhof, D., Rapp, S., Fasel, U., Gaunaa, M., Schmehl, R.: Reference Design and Simulation Framework of a Multi-Megawatt Airborne Wind Energy System. Journal of Physics: Conference Series 1618, 032020 (2020). https://doi.org/10.1088/1742-6596/1618/3/032020

Eijkelhof, D., Schmehl, R.: Six-Degrees-of-Freedom Simulation Model for Future Multi-Megawatt Airborne Wind Energy Systems. Renewable Energy 196, 137–150 (2022). https://doi.org/10.1016/j.renene.2022.06.094

Fagiano et al. 2022: Autonomous Airborne Wind Energy systems: accomplishments and challenges, https://www.annualreviews.org/content/journals/10.1146/annurev-control-042820-124658

Filippo Trevisi, Alessandro Croce (2024). Given a wingspan, which windplane design maximizes power?. Journal of Physics: Conference Series.CiteDOI

Ghassan Kharbeet, Hanieh Khodaei, Victor Egbert Scholten, J. Roland Ortt (2024). Business Model Dynamics During the Growth Stages of Technology-Based Start-Ups. Academy of Management Proceedings.CiteDOI

Guillore et al. (2023), Eco-conscious design evaluation of Airborne Wind Energy Systems using Life Cycle Assessment, https://zenodo.org/records/8020873

https://docs.nrel.gov/docs/fy21osti/79992.pdf

https://research-hub.nrel.gov/en/publications/airborne-wind-energy/

Inés Coca-Tagarro (2024). Site Identification Analysis for AWE Devices. A case study in Ireland. https://zenodo.org/records/14825339

Inés Coca-Tagarro (2024). Site Identification Analysis for AWE Devices. A case study in The Netherlands. https://zenodo.org/records/14886726

Jesse I. S. Hummel, Tijmen S. C. Pollack, Dylan Eijkelhof, Erik-Jan Van Kampen, Roland Schmehl (2024). Power Smoothing by Tether Force Control for Megawatt-Scale Airborne Wind Energy Systems. Journal of Physics: Conference Series.CiteDOI

Johannes Peschel, Eduard Ijsselmuiden, Sweder Reuchlin (2024). Kitepower Wind Energy: RWE Test Site Insights. 10th international Airborne Wind Energy Conference (AWEC 2024): Book of Abstracts.CiteURL

Joshi, R., Kruijff, M., Schmehl, R. (2023), Value-Driven System Design of Utility-Scale Airborne Wind Energy. Energies 16(4), 2075. https://www.mdpi.com/1996-1073/16/4/2075

Joshi, R., Terzi, D. v., Kruijff, M., Schmehl, R.: Techno-economic analysis of power smoothing solutions for pumping airborne wind energy systems. Journal of Physics: Conference Series 2265, 042069 (2022). https://doi.org/10.1088/1742-6596/2265/4/042069

Julian Quick, Juan Pablo Murcia Leon, Polyneikis Kanellas, Sumanth Yamujala, Kaushik Das, Matti Koivisto (2024). Surrogate-based modeling and sensitivity analysis of future European electricity spot market prices. Electric Power Systems Research.CiteDOI

Kirsten Coutinho et al. (2024). Life cycle assessment of a soft-wing airborne wind energy system and its application within an off-grid hybrid power plant configuration. https://repository.tudelft.nl/record/uuid:55533d19-21e1-4851-bf7c-7f3af008aaaa

Kristian Petrick (2024). Policy and Regulatory Outlook Towards AWE Deployment. 10th international Airborne Wind Energy Conference (AWEC 2024): Book of Abstracts.CiteURL

Launer et al. (2023), Europe-wide energy system scenarios for wind deployment areas. Deliverable D2.1. JustWind4All. https://justwind4all.eu/wp-content/uploads/2023/12/JW4A-D2.1.-Europe-wide-energy-system-scenarios_v2.pdf

Lukas Ranzinger, Stephanie Uhrig, Stefan Tenbohlen (2024). Analysis and Modeling the Frequency Response of Rotating Machines Regarding Fault Diagnosis Using SFRA. IEEE Transactions on Energy Conversion.CiteDOI

Mac Gaunaa (2024). Lifting-Line Aerodynamics for Airborne Wind Energy on a Prescribed Path. 10th international Airborne Wind Energy Conference (AWEC 2024): Book of Abstracts.CiteURL

Mac Gaunaa, Ang Li, Michael McWilliam, Mark Kelly (2024). Lifting-Line Aerodynamics for Airborne Wind Energy on a Prescribed Path. 10th international Airborne Wind Energy Conference (AWEC 2024): Book of Abstracts.CiteURL

Mark Kelly, Mac Gaunaa, Michael McWilliam (2024). Towards Atmospheric Event-Driven Loads for Rigid AWES. 10th international Airborne Wind Energy Conference (AWEC 2024): Book of Abstracts.CiteURL

Mark Schelbergen, Roland Schmehl (2024). Swinging motion of a kite with suspended control unit flying turning manoeuvres. Wind Energy Science.CiteDOI

Moutel, M. (2025). Site Identification Analysis for AWE Devices. A case study in France. Interreg NWE DEM-AWE project forthcoming)

Nikolaus Vertovec, Sina Ober-Blöbaum, Kostas Margellos (2024). Safety-Aware Hybrid Control of Airborne Wind Energy Systems. Journal of Guidance, Control, and Dynamics.CiteDOI

Olalekan Omoyele, Maximilian Hoffmann, Matti Koivisto, Miguel Larrañeta, Jann Michael Weinand, Jochen Linßen, Detlef Stolten (2024). Increasing the resolution of solar and wind time series for energy system modeling: A review. Renewable and Sustainable Energy Reviews.CiteDOI

Peter Kinsley (2024). Standardisation and Certification of Airborne Wind Energy. https://zenodo.org/records/13986343

Petrick et al. 2025: Energy Read: Securing local support for AWE projects – a guide for project developers. JustWind4All, https://justwind4all.eu/wp-content/uploads/2025/10/AWEEnergy-Read_V5.pdf

Poland, J. A. W., Schmehl, R. (2023), Modelling Aeroelastic Deformation of Flexible Membrane Kites. Energies 16(14), 5264. https://doi.org/10.3390/en16145264

Poland, J.A.W. and Schmehl, R.: Modelling Aero-Structural Deformation of Flexible Membrane Kites, Energies, 16(14):5264, 2023. https://doi.org/10.3390/en16145264

Porta Ko, A., Smidt, S., Schmehl, R., Mandru, M. (2023), Optimisation of a Multi-Element Airfoil for a Fixed-Wing Airborne Wind Energy System. Energies 16(8), 3521. https://doi.org/10.3390/en16083521

Reuchlin, S., Joshi, R., Schmehl, R. (2023) Hybrid Power Systems for Off-grid Applications Using Airborne Wind Energy. Energies 16(10), 4036. https://doi.org/10.3390/en16104036

Rishikesh Joshi, Filippo Trevisi (2024). Reference Economic Model for Airborne Wind Energy Systems. IEA Wind TCP Task 48.CiteDOI

Rishikesh Joshi, Roland Schmehl, Michiel Kruijff (2024). Power curve modelling and scaling of fixed-wing ground-generation airborne wind energy systems. Wind Energy Science.CiteDOI

Salma, V., Schmehl, R. (2023), Operation Approval for Commercial Airborne Wind Energy Systems. Energies 16(7), 3264. https://doi.org/10.3390/en16073264

Schmidt et al. (2022), The Social Acceptance of Airborne Wind Energy: A Literature Review. https://www.mdpi.com/1996-1073/15/4/1384

Schmidt et al. (2024), How do residents perceive energy-producing kites? Comparing the community acceptance of an airborne wind energy system and a wind farm in Germany. Energy Research & Social Science, Volume 110, 103447, https://doi.org/10.1016/j.erss.2024.103447

Schmidt, H., Renatto M. Yupa-Villanueva, Daniele Ragni, Roberto Merino-Martínez, Piet Van Gool, Roland Schmehl (2025). A listening experiment exploring the relationship between noise annoyance and sound quality metrics for airborne energy systems. Wind Energy Science Discussions.CiteDOI

Schmidt, H.,. Valentin Leschinger, Florian J. Y. Müller, Gerdien De Vries, Reint Jan Renes, Roland Schmehl, Gundula Hübner (2024). How do residents perceive energy-producing kites? Comparing the community acceptance of an airborne wind energy system and a wind farm in Germany. Energy Research & Social Science.CiteDOI

Sommerfeld, M. Dörenkämper, J. De Schutter, C. Crawford (2023), Impact of wind profiles on ground-generation airborne wind energy system performance. Wind Energy Science, 8(7), 1153–1178. https://doi.org/10.5194/wes-8-1153-2023

Stefanie Thoms, Kristian Petrick, Jesús Carballo (2024). Preparing AWES Deployment by Onboarding RE Stakeholders with Regards to Social Acceptance. 10th international Airborne Wind Energy Conference (AWEC 2024): Book of Abstracts.CiteURL

Tareg Mohammed, Espen Oland, Lorenzo Fagiano (2024). Fault Tolerant Flight Control for the Traction Phase of Pumping Airborne Wind Energy Systems. International Journal of Control, Automation and Systems.CiteDOI

Tareg Mohammed, Jørgen Busk, Espen Oland, Lorenzo Fagiano (2024). Large-Scale Reverse Pumping for Rigid-Wing Airborne Wind Energy Systems. Journal of Guidance, Control, and Dynamics.CiteDOI

Thedens, P., Schmehl, R.: An Aero-Structural Model for Ram-Air Kite Simulations. Energies 16(6), 2603. March 2023. https://doi.org/10.3390/en16062603

Thimm, L., Schelbergen, M., Bechtle, P., Schmehl, R.: The Airborne Wind Energy Resource Analysis Tool AWERA. In: the 9th international Airborne Wind Energy Conference (AWEC 2021) Book of Abstracts, 22-24 June 2022, Milan. http://resolver.tudelft.nl/uuid:ba0c7fb2-baff-4110-9a51-c27a8498663b

Trevisi et al. (2023), Refining the airborne wind energy system power equations with a vortex wake model, Wind Energy Science, 8, 1639–1650. https://doi.org/10.5194/wes-8-1639-2023

Trevisi, F., Riboldi, C. E. D., Croce, A. (2023), Refining the airborne wind energy system power equations with a vortex wake model, Wind Energ. Sci., 8, 1639–1650. https://doi.org/10.5194/wes-8-1639-2023

Van Hagen, L., Petrick, K., Wilhelm, S., Schmehl, R. (2023) Life Cycle Assessment of a Multi-Megawatt Airborne Wind Energy System. Energies 16(4), 1750. https://doi.org/10.3390/en16041750

Vos (2023), A whole-energy system perspective to floating wind turbines and airborne wind energy in The North Sea region. MSc Thesis, Delft University of Technology. https://repository.tudelft.nl/islandora/object/uuid%3A7bda9c95-1aec-40fb-a585-1e0af8b743bb

Vos, Hidde , Francesco Lombardi, Rishikesh Joshi, Roland Schmehl, Stefan Pfenninger (2024). The potential role of airborne and floating wind in the North Sea region. *Environmental Research: Energy*.CiteDOI