Chapter 26

A Roadmap Towards Airborne Wind Energy in the Utility Sector

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Abstract The development path of the Ampyx Power airborne wind energy system is described. It is intended for the utility sector and large-scale grid connection. The technology generates energy by flying a tethered glider-aircraft attached to a ground-based generator following a crosswind pattern as the tether unwinds under high tension, and rewinds under near-zero tension. The benefits, drawbacks and decision rationales of major design choices are discussed: crosswind operation, rigid aircraft concept, ground-based generator. The development plan is shared and an indication is given how we defined our performance targets by prototype tests and extrapolations based on validated dynamic simulation. The development plan is to first build a system aimed to demonstrate safety and autonomy. Next, the first commercial system shall minimize Levelized Cost of Energy (maximizing the customer's return on investment). A larger system then maximizes productivity (maximizing the customer's net profit). Offshore operation is targeted. Safety levels are continuously improved to enable co-use of the land under the tethered aircraft.

26.1 Introduction

Ampyx Power develops a novel airborne wind energy system (AWES) which will eventually allow sustainable production of power at lower costs than fossil-fueled alternatives. The availability of such technology will likely trigger a paradigm shift in the electricity sector. The AWES converts wind power into mechanical power by having an autopilot-controlled glider aircraft creating pull on a tether by flying repetitive crosswind patterns at an altitude of 200 to 450 m, as described in [10] and illustrated in Fig. 26.1 (left). Conversion to electrical power happens in a ground-based generator from which the tether is extracted. Once the tether has

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Fig. 26.1 Comparison of Ampyx Power's 2 MW AWES with typical 2 MW wind turbine in flight (left) and in storage (right)

been extracted to full length, the glider aircraft is controlled to glide back to the pattern starting point, during which phase the tether is retracted. During this reel-in phase, tether tension is minimal and power consumption is only a fraction of the power produced during the reel-out phase. Automatic land and launch cycles are made possible through a platform-based solution. The chapter will address Ampyx Power's ambitions with this concept and how we intend to achieve them, in terms of our development plan as well as our sizing rationale.

Ampyx Power targets the utility market with its AWES, therefore our concept firstly will have to be able to complement or compete with conventional wind turbine plants. Following an introduction into the key architectural features of our concept, a comparison against the conventional wind turbine performance is provided. Ampyx Power recognizes that one of the key additional challenges of developing AWE technology is securing the required levels of safety and reliability for the fully autonomous operation in a large range of weather conditions. The means in which we intend to meet these are described. With the Ampyx Power mindset and ambition clarified, we describe our current status and development plan, with a focus respectively on the aircraft/power generator combination and the launch and land platform. The second part of this chapter describes the sizing methodology that we have developed, which is based on a tool chain including an aero-structural model, a performance model and a cost model.

In Sect. 26.2 we present the overall development plan of our company. In Sect. 26.3 we detail this plan by outlining key architectural choices, design processes and certification, explaining the development status and the pursued approach as well as our strategy for launching and landing. In Sect. 26.4 important considerations about the sizing for the commercial system are discussed, such as the aerodynamic and structural models, the performance model and the trade-offs and finally the cost model and the prediction of the achievable LCoE. Conclusions are discussed in Sect. 26.5. The preliminary content of the present chapter has been presented at the Airborne Wind Energy Conference 2015 [8].

26.2 The Ampyx Power AWES Development Plan

The main architectural design choices that define the Ampyx Power AWES are:

- crosswind flight rather than static,
- a rigid wing rather than a flexible kite,
- ground-based generator rather than on-board,
- utility-scale power generation rather than off-grid.

Table 26.1 highlights the benefits and drawbacks for each of these choices.

The aircraft makes use of a platform for its landing rather than e.g. a runway or some dynamic capturing system (such as a rotating arm). Even if we do not consider this a fundamental constraint for the AWES concept, we believe the platform landing has fundamental advantages, further detailed in a dedicated section below. We have rather firmly settled on a single tether solution rather than a double tether.

Architectural choice	**Ampyx Power considerations**
Crosswind	Crosswind systems much more efficiently convert wind power than static systems [9].
Rigid wing	Compared to a flexible system (kite). The reel-in phase is more efficient due to an aircraft's natural and fast glide dynamics vs. drag behavior of kite. This greatly improves cycle efficiency[a]. Rigid wing dynamic control has less degrees of freedom due to less wing flexing. Rigid wing control can be reliably performed also following tether rupture. A rigid wing can be designed for a high lift coefficient compared to a kite. Hence the same power can be generated with a more compact solution—though likely more heavy/costly. Composite structures can be designed to be damage tolerant and should meet a 20-year lifetime requirement. Lifetime is then orders of magnitude longer than that of flexible kites that typically survive only for hundreds of hours of operation [1, 4]. Regular replacement of a kite is costly and creates downtime.
Ground-based generator	An airborne generator would have to be custom designed and mass optimized, so likely costlier than off-the-shelf ground-based equipment. It puts high value in the air, at higher risk of loss in case of a crash. For a ground-based generator the tether does not need to carry (significant) current and can be thinner (less drag losses) and simpler (lower cost). However, due to the reel-in reel-out cycles, it will wear faster. The pumping winch is more complex than one for on-board power generation. Also, efficiency is lost since during reel-in no energy is generated. Furthermore, the on-board generator can double as oversized propulsion and allow for relatively simple spot landing techniques [12].
Utility scale	It is Ampyx Power's belief that a significant commercial potential lies in providing large amounts of energy at low cost. We also think that off-grid solutions may well be viable, however we think that such a solution requires its own dedicated design effort not necessarily applicable to a utility-scale solution. It would thus be for Ampyx Power more of a distraction on the path to a utility-scale system than a stepping stone.

[a] We define cycle efficiency as ratio of energy that is actually generated over reel-out/reel-in cycle and energy the system would generate when only reeling out over the same period of time.

Table 26.1 Key design choices for the Ampyx Power AWES

We realize that a double tether provides some safety through redundancy but the increased wear and replacement of tether material that comes with it would drive up the energy price. At the same time, the doubled tether drag would contribute to additional power generation losses, as shown in Fig. 26.11. A double tether would also allow (part of) control of the wing dynamics to be done from the ground, so there could be placed on-board less costly and less heavy avionics and actuators. Some avionics there would still be required such that the aircraft can be autonomously controlled and safely landed following tether rupture. However, the control and systems on-ground would be more complex and control would be less direct, so likely less precise.

Other design choices we have made for the current prototype are considered subject to trade-off and may vary from concept to concept, such as:

- the lemniscate pattern (figure of eight) vs. ellipse,
- the single-point tether-aircraft connection without bridle,
- the rather conventional aircraft layout and typical aircraft controls,
- on-board power generation for the avionics rather than provision of power through the cable.

26.3 Ampyx Power AWES Versus Conventional Wind Turbines

26.3.1 Key Architectural Choices

In the classical wind turbine concept only a small fraction of the structure (namely the blade tips) generate the majority of the power output. In contrast (as with all AWE crosswind concepts) the full wing span of the AWES aircraft is exposed to the high speed of the air flow that is obtained by its crosswind trajectory [9, Fig. 1]). Therefore, every part of the wing structure generates the associated high level of lift. A wing of size less than a single turbine blade generates the same power as the whole wind turbine. The material usage is thus highly effective.

Furthermore, there is almost no torque on the foundation, so that can be less massive than for conventional wind turbines. This is particularly valuable for offshore applications, where the generator can be placed on a spar rather than a pole, as illustrated in Fig. 26.2. No data exists yet on wake losses for large rigid-wing AWE farms. Two factors suggest these losses will be quite limited in comparison to conventional turbines. The smaller 'blade' area will disturb less air (though more intensely) and this disturbance is distributed through the flight pattern over a much larger vertical spacing.

With synchronized systems positioned closely together, our commercial design is expected to eventually achieve a park level power density in the range of 10 to 25 $\mathrm{MW/km^2}$ depending on the system sizing. For prudence reasons (obtaining flight hour statistics), initial parks will operate at lower density. A set-up of an initial commercial park of AWE systems should have a facility density of slightly better than

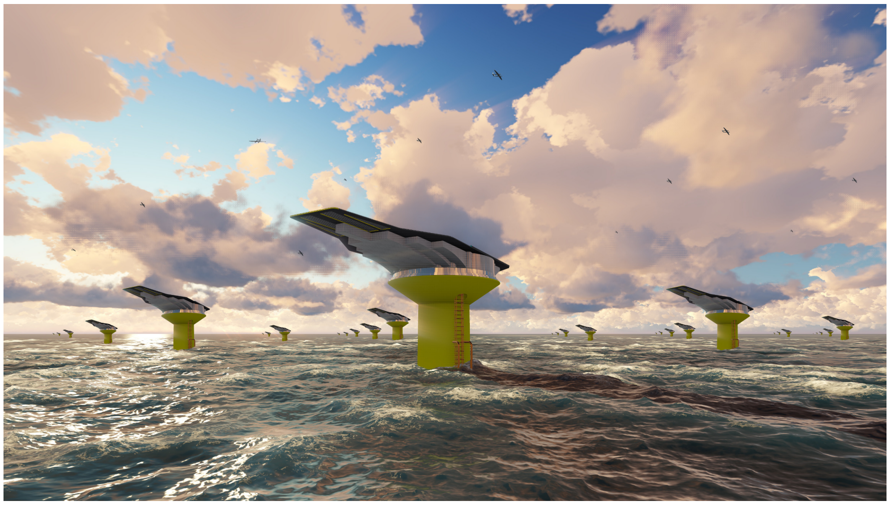


Fig. 26.2 Ampyx Power offshore AWES impression

$1/L^2$, L being the maximum tether length. During power generation, the aircraft trajectories do not interfere with each other, and some margin can be appreciated, as depicted in Fig. 26.3. During launching and landing maneuvers that exit the footprint, some additional space would need to be created. For this, surrounding pattern movements could be narrowed, shifted and/or temporarily paused (loitering). Later, a packing of about $2/L^2$ to $3/L^2$ should be achievable, requiring synchronization of the patterns to within half the pattern width and allowing some overlap of the tether footprints. Even higher densities can be achieved using a cylindrical rather than conical volume constraint for the 3D flight path [5].

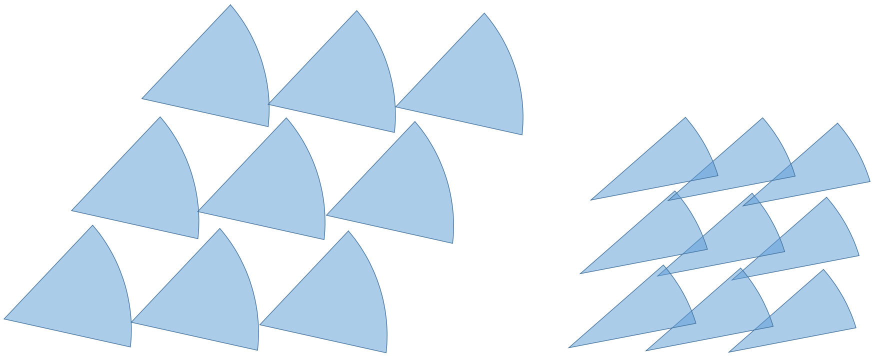


Fig. 26.3 Tether footprints for a given wind direction in a plant set-up. Left: a packing density of $1.2/L^2$, without pattern footprint overlap. L being the maximum tether length Right: a packing density of $\sim 2.7/L^2$, with flight overlap allowed over the bottom half of the downwind tether as well as synchronization required within half a pattern width (half a footprint shown)

26.3.2 Processes and Certification

Ampyx Power has opted to engage with authorities to identify suitable civil aviation standards and recommended design processes, including airworthiness, design organization and operational aspects, with the goal to achieve the required reliability and safety for commercial operation as well as certification (Table 26.2 and Chap. 29 in this book). We believe these design processes are enabling and have a number of proven benefits. They result in more traceability in case of issues and increase transparency of the project. Hence they greatly aid the convergence of design and provide better learning and improvement possibilities. This should result in better planning capability and lower end-to-end development cost. A certified design and production has furthermore the obvious benefit that the design can be produced in large numbers with only functional testing required for each delivered item rather than full verification.

Adhering to such standards can be challenging and requires some investment. In order to make it possible for a small company like Ampyx Power to provide full design traceability, support configuration management and process-based engineering, we believe a single place for our data and a single interface for the whole team is the way forward. Therefore, we have commissioned the Polish-based company Xignum to develop a tool tailored to the needs of AWE certification, cov-

Permitting element	**Description**
E.Y013-01	Current European Aviation Safety Agency (EASA) policy for Unmanned Aerial Systems (UAS), deemed applicable as our system is regarded a tethered UAS. It prescribes the tailoring of a suitable Certification Specification and an appropriate systems safety analysis.
CS-22	Certification Specification for sailplanes (gliders) which we have used as a starting point for tailoring, since our aircraft, once off the tether (the most risky situation) behaves as an unmanned glider with limited range and kinetic energy.
SC-RPAS 1309-01 Issue 2	Safety standard for Very Light Aircraft (VLA) classes of Remotely Piloted Aircraft Systems (RPAS) that we selected as starting point.
ED-79A	Accepted means of compliance for aircraft design processes (planning, requirements derivation, validation, verification, safety analysis, configuration management, product assurance, certification)
DO-178C	Accepted means of compliance for software design process. We will tailor this with the help of selected software standards of the European Cooperation for Space Standardization (ECSS).
AS9100	Aerospace supplier organizational quality system, which we use as a guideline.
(A)DOA	(Alternative to) Design Organization Approval: organizational processes, mainly product assurance and certification that should be in place when a commercial product is designed. Not required for experimental/development planes.
Operational requirements	The National Aviation Authority (NAA) requires on the operational side Safety management system, operations manual, pilot training

Table 26.2 Overview of some permitting standards being implemented by Ampyx Power

ering all required project and process data, including e.g. workflows, versioning and data interrelations. Some common problems and the approach by Xignum are shown in Table 26.3. Its specifications are based on experience with space projects [7], the aerospace industry standard AS9100 [11], the European Cooperation for Space Standardization (ECSS), as well as the aeronautical design guideline ED-79A (Table 26.2). Note that this solution is available to the AWE community through Xignum.

Team issue during development	**Xignum approach**
Why are we doing this exactly again?	Customer requirements
Am I doing the right thing?	Requirements
Am I doing the thing right?	Validation & Verification workflows
How reliable is this document?	Document approval workflow
Where is the most recent version of this document?	Document access & version control
Did not someone think of this before?	Decision (Trade-Off)
We really better take action now and not forget to think of this next time.	Risk, Lesson Learned work flows
Why again did we choose this option?	Decision (Trade-Off)
I am not quite sure about this but don't want to wait for the input to arrive. How can I continue my work?	Decision (Assumption) workflow, Task (To Be Confirmed / To Be Determined).
Where is this piece of scratched hardware?	Inventory management, Assembly
What software version and parameter settings did we use in that test flight again?	Software version control (GIT link), test logs
This is never going to work, in my opinion. But if you insist on going ahead...	Risk
I am not sure we agree on which thing should do what exactly.	Design tree, function definitions
I need to manufacture the exact same piece of hardware as 3 months ago	Manufacturing Reference
What changed since that meeting where we all agreed?	Baseline definition, history log
There is a problem with this document, hardware that should be handled properly	Review Item Disposition (RID), Task (approval workflow), Non-conformance Report (NCR)
How do we know whether it is safe enough?	Safety analysis (Functional Hazard analysis, Fault Tree diagram, Failure Mode and Effect Analysis)
What is the next step and who should do it?	Workflow Which inventory items exactly where in that test and where is the test data? Assembly, Validation & Verification Plan

Table 26.3 Some common problems encountered in complex development projects relieved through the Xignum tool

26.3.3 Ampyx Power AWES Development Status and Approach

Ampyx Power currently operates 2 prototypes in a test field in The Netherlands, for which it has obtained type registration and an exemption (license to operate) from the national authorities based on a safety analysis, implementation of a safety system, pilot training and operations manual. Representative footage is shown in Fig. 26.4.

The aircraft are designated AP-2A1 and AP-2A2, and can produce about 20 kW net power. These 5.5 m prototypes serve to demonstrate the principle of a fully automatic operation (power generation → land → launch → power generation), as well as to raise the technology readiness level. AP-2 has a single autopilot. Its safety is based on a mitigation (of autopilot failure) through redundant remote control piloting. AP-2A1 is equipped with propulsion (for landing and take-off from a compact platform). AP-2A1 has an on-board power generator (small turbine installed on top of the fuselage) to power the actuators and avionics and thus provide the capability

Fig. 26.4 AP-2A aircraft, 90 kW generator and control center

for unlimited flight. Autonomous flight without intervention has been demonstrated for flights of over 2 hours. Net power production has been demonstrated [10], and matched with simulation data.

The next steps in Ampyx Power's AWES development are the certifiable pre-commercial prototype AP-3 (200 kW) and the to-be certified commercial version AP-4 (2 MW). These systems shall be operational in the coming few years. Table 26.4 sketches out some details for this development plan.

The AP-3 is to demonstrate full autonomy, design for reliability and safety, as well as predictability of performance and of cost. During its operation we aim to evidence high cycle efficiency, and low maneuvering and drag losses. It shall demonstrate operation at high g-load. It also serves as learning platform to meet the challenges of site development, grid connection, maintainability and 24/7 operations.

The AP-3 design shall be such that no single failure is to lead to loss of life or (if in any way possible) to loss of the aircraft. The probability of a combination of failure conditions leading to loss of life shall be extremely remote. Since the necessary avionics for full autonomy under such constraints are rather complex, they will be implemented in steps during the AP-3 verification phase.

AP-3 is to meet reliability requirements using a triple-redundant autopilot. However, as the individual autopilots are based on the same hardware and software, a common cause failure cannot be prevented (or in safety wording, independence

	AP-2 Proof-of-concept	**AP-3** Commercial prototype	**AP-4A** Utility-scale prototype	**AP-4B/C** Utility-scale commercial	**AP-5(TBD)** Utility-scale commercial
Development	2011–2015	2014–2018	2018–2020	TBD	TBD
Wingspan $[\mathrm{m}]$	5.5	12	35	35	50
Mass $[\mathrm{kg}]$	35	400	3500	3000	5000
Windturb. eq.$[\mathrm{MW}]$	0.01	0.2	2.0	2.0	4.0
Density $[\mathrm{MW/km}^2]$	-	0.5	5	10 – 15	15 – 25
Co-use	Limited	Limited	Limited	Yes	Yes
Offshore	No	No	Yes	Yes	Yes
Optimized for	Breadboarding	Autonomy & safety demo	LCoE	LCoE	Plant output
Technology (mostly)	Custom	COTS	COTS Aircraft Custom ground segment	COTS Aircraft Custom ground segment	Custom
Safety mitigation	RC Pilot	Tether	Tether	Independent back-up autopilot	Independent back-up autopilot
Certification target / policy	Exemption (NAA)	Permit (EASA E.Y0.13)	Permit (EASA E.Y0.13)	Certified (EASA E.Y0.13)	Certified (EASA CoO)

Table 26.4 Ampyx Power AWES generations AP2 (in operation), AP3 (under development), AP4 (commercial version), technological approach and current estimates of performance. COTS: Commercial Off-The-Shelf. TBD: To Be Determined. CoO: Concept of Operations

cannot be claimed). Hence mitigations need to be in place. Firstly, the general public will not be allowed underneath the operating aircraft. The tether is then to secure that, upon autopilot failure, a "safe" crash would result within known radius. Such a crash would still be a costly event. Thus, during early verification, as for AP-2, a pilot will be available to take over control when necessary. In later flights, an independently developed emergency landing software will be added, allowing us to fly more comfortably without pilot oversight.

AP-3 size is limited to a 12 m wing span as deemed practical for a developmental aircraft. The wing aspect ratio is selected for high power output per kilogram of wing mass (Figs. 26.5 and 26.12). With a mass of about 300 kg, the AP-3 is designed to sustain 42 kN operational tether tension.

We have initiated the certification trajectory with EASA for AP-3, as a stepping stone to AP-4. It is foreseen though that only a small number of units of AP-3 will fly, and this will be under a permit as a developmental aircraft.

It is noted that uptime and reliability can be analyzed and improved by strict design rigor but have eventually to be demonstrated in the field and will undoubtedly need to improve over time as flight hours and operational experience accumulates. An extended flight campaign of AP-3 may be used for this, alternatively, this objective can be met by the early AP-4 models.

The AP-4 is scaled with the target to operate at a minimal Levelized Cost of Energy (LCoE). For commercial viability this should be well below that of conven-

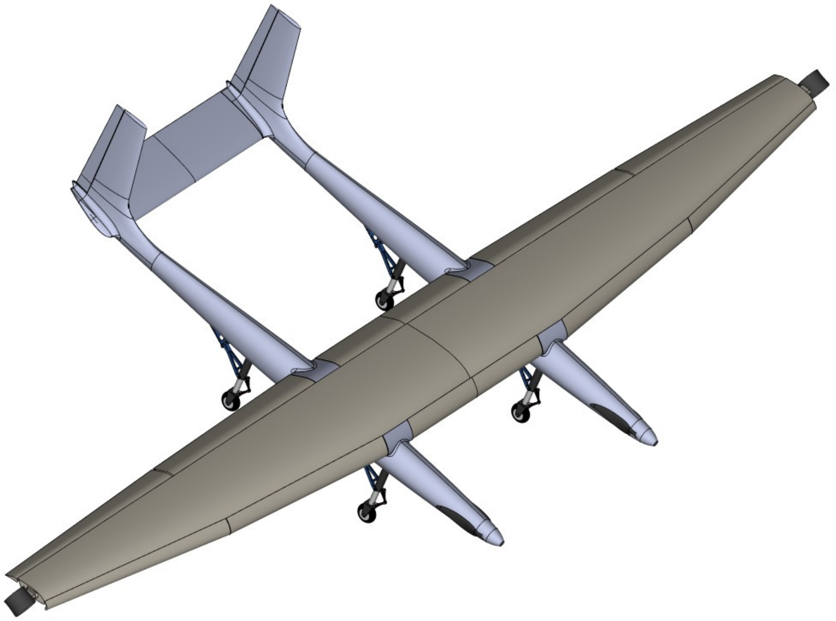


Fig. 26.5 AP-3 conceptual sketch (Autumn 2015)

tional wind energy, and our cost model predicts this can indeed be achieved (see section below for more details). AP-4 shall be ready for offshore deployment. The generator is to be optimized to limit conversion losses.

Three versions of AP-4 are foreseen over time (4A,B and C): to increase safety, and to reduce manufacturing and maintenance cost.

AP-4A will still be an experimental system with its power output already at final commercial levels (2 MW). It is a much larger system than AP-3, but shares the same avionics, control software and autonomy.

AP-4B will be the first certified system, and is to be deployed on a large scale. Its aircraft will feature design independence added to the redundancy in the avionics, which would make it possible, eventually, to allow the general public underneath the operating hardware. AP-4B is otherwise identical to AP-4A. Cost is lowered due to better deals with suppliers (economy of scale).

AP-4C would be the cost optimized version of AP-4. Based on flight and maintenance experience, we can slowly steer away from initially conservative values for component quality, safety margins and material grades. Furthermore, we would start developing our own production lines for selected components, systems and materials, in order to further benefit from our economy of scale and reduce system costs. Its LCoE shall beat the price of the traditional fossil fuel alternatives.

AP-5 can be roughly expected to be double the size of AP-4 and should optimize for the customer's net benefit, given availability of a limited plant area or number of systems. Its sizing is still immature. It depends on the projected energy price vs. cost, the packing density that can be achieved (scaling of tether length with wing size), scaling of wing mass with size and possibly, for the case of large offshore farms, scaling of wake losses.

26.3.4 Launching and Landing

The Launch and Land (L&L) solution is an immensely challenging part of the AWE system, that we have managed to cover using a combination of conventional technologies, adapted to our purpose. The requirement for a compact L&L system derives from the need to perform launch and land:

- in rough terrain and, eventually, at sea;
- for any wind direction;
- without disconnecting the tether;

An extensive conceptual trade-off has been performed. A conventional field landing for an AWES aircraft would require about 130×100 m runway field to cover all wind directions and wind levels. For commercial operation, that is not a practical option. A rotor-type vertical lift solution such as employed in [12] is considered not viable for Ampyx Power's ground-based generator concept at utility scale. A solution where the aircraft is gently captured by some type of controlled interceptor whilst still in the air is considered technologically challenging and not sufficiently robust.

A platform solution for a compact landing, rotated into the wind, has a number of benefits, when compared to the main alternatives. The L&L platform hardly scales with aircraft size. So the larger the aircraft, the smaller, relatively, will be the platform. Our requirement, derived from the cost model, is that the platform shall be shorter than the wingspan of our commercial model, the AP-4.

Platform launch and land can be achieved using conventional technology, such as a catapult and an arresting line (as we are applying for AP-2) or a net. Alternatively, we can use the tether to accelerate (as in a standard winch launch) and even to decelerate the aircraft—it is already attached. A complication is that the L&L shall be fully autonomous, and not require human intervention, even for post-landing guidance towards the launch position. This makes the use of e.g. a conventional net impractical for nominal landing. Furthermore, the aircraft shall be kept restraint until the next launch, such that gusts do not levitate the aircraft off the platform and cause damage.

The platform concept allows to use alternative implementations as introduced above for the mitigation of single failures, such as tether release, failure of propulsion or failure of one of the platform systems itself. Our approach is that any functional failure that can happen that has a major consequence (risk to damage the aircraft) is mitigated by a secondary solution.

Expressed in functional terms of the ED-79A design process and safety approach, the solution adopted by Ampyx Power can be described schematically as in Fig. 26.6. An impression of the resulting design is provided in Fig. 26.7. A detailed description of functionality will be subject of a future publication.

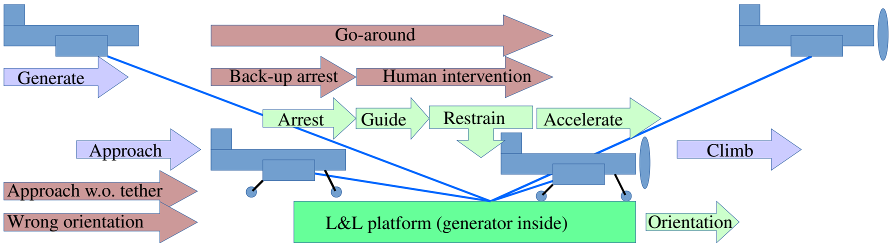


Fig. 26.6 Autonomous Launch and Land concept based on safety considerations. Mission phases Generate, Approach and Climb connect to the Land and Launch phases, which are covered by the required functions Arrest, Guide (to restrain position), Restrain and Accelerate. Furthermore, some form of Orientation with the wind is required to deal with any wind direction. Some indicative failures/mitigations to be covered are indicated as well. Whereas the overall functionality and safety is thus defined, each function in it can be implemented by one of several existing technologies depending on the scaling of the system (in our case AP-2, AP-3, AP-4 etc.)

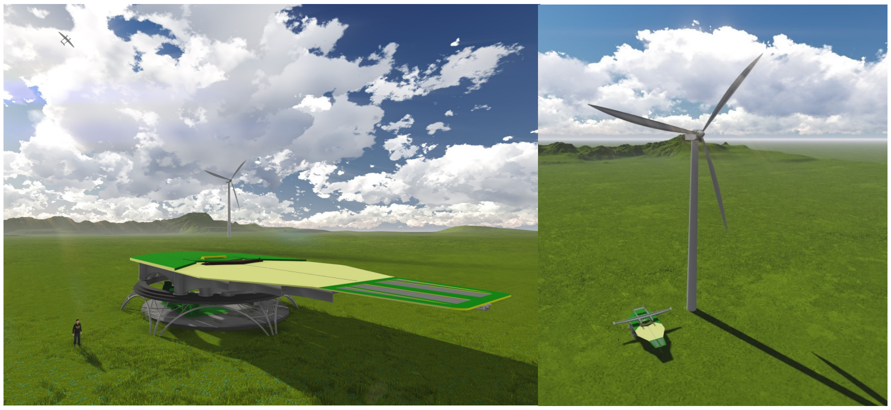


Fig. 26.7 Impression of the AP-4 (2 MW) in comparison to a conventional 2 MW wind turbine with aircraft in operation (left) and in storage configuration on the platform (right)

26.4 Sizing of a Commercial System

An integrated set of sizing tools has been developed by Ampyx Power for a preliminary sensitivity analysis to understand the primary cost factors and perform first order sizing of the AP-3 and AP-4 designs. Figure 26.8 shows the main elements and parameters involved. The primary loop is that, given the necessary constraints, tether tension and wing planform are determined to achieve optimal LCoE (AP-4), or, employing also a secondary loop, to achieve optimal energy production given a

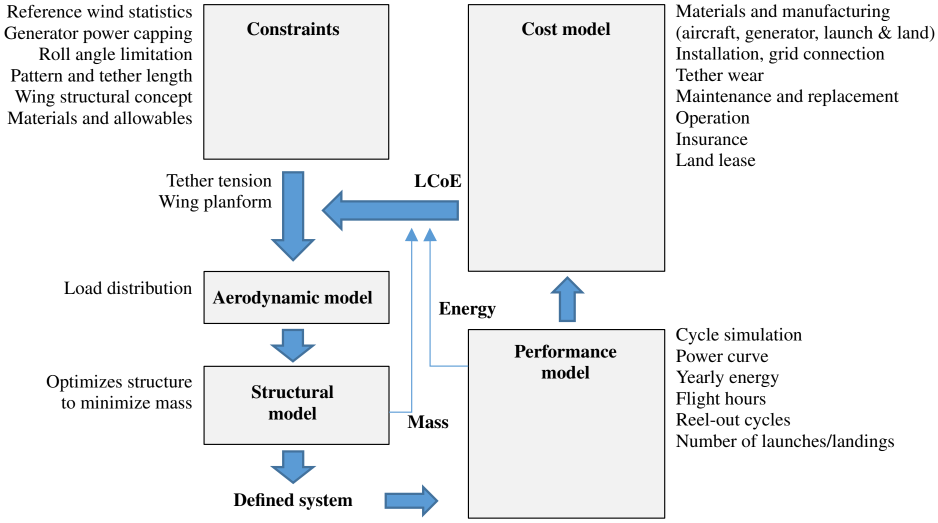


Fig. 26.8 Ampyx Power toolbox and methodology for system sizing to minimal LCoE

certain mass or size limitation (AP-3). Within each cycle, tether tension and wing planform are fed into an aerodynamic and a structural model. This defines a system for which energy output and LCoE are estimated.

26.4.1 Aerodynamic and Structural Model

The structural optimization model is centered around the optimization of wing mass for a given cable tension, from which, with simpler models, the total aircraft mass is estimated. It has a parametric description of the wing structural cross-section (spars, spar caps, skin), its dimensions (aspect ratio, tapering etc.) and its mass breakdown (composites, honeycomb, glue etc.). Based on a non-linear lifting-line aerodynamic model the loads and stresses are computed and parameters are adjusted to achieve optimal mass within given boundary constraints (allowable for torsional stiffness, wing tip bending, stress/strain levels for fatigue, buckling, breaking), as illustrated in Fig. 26.9. The model has been validated for a number of data points using hand calculations as well as Computational Fluid Dynamics (CFD) and Finite Element Methods (FEM). To complete the mass estimate, the avionics mass is added as a constant. The fuselage is estimated as a fraction of the wing mass. Paint, glue, cabling, actuators and equipment masses are estimated based on interpolation of properties of components available on the market.

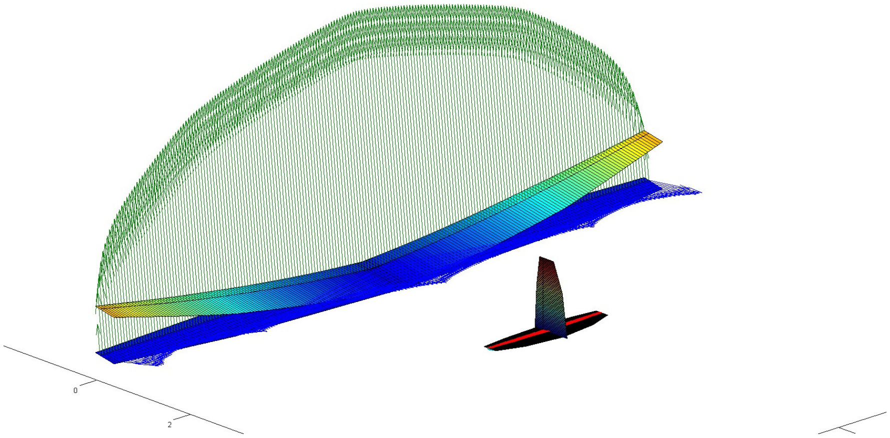


Fig. 26.9 Ampyx Power sizing tool computes for wing and tail surfaces the distribution of aero loads (shown as vectors) and then the resulting deflection of the structure (shown in color coding), based on a reference layout (spars, caps, skin), material properties and wall/skin thickness

26.4.2 Performance Model and Trade-Offs

The performance predictions of the Ampyx Power AWES are based on a number of analyses:

- Simulation in 6-DOF using detailed modeling of aircraft flight characteristics and controller, as visualized in Fig. 26.10. A flexible tether model is included [10].
- Prototype flights using AP-1 and AP-2, as shown in Fig. 26.4, matching closely the results of step 1 [10].
- Fast simulation using three independently developed cross-validated point mass tools [3]. This simulation is part of the integrated sizing toolset.

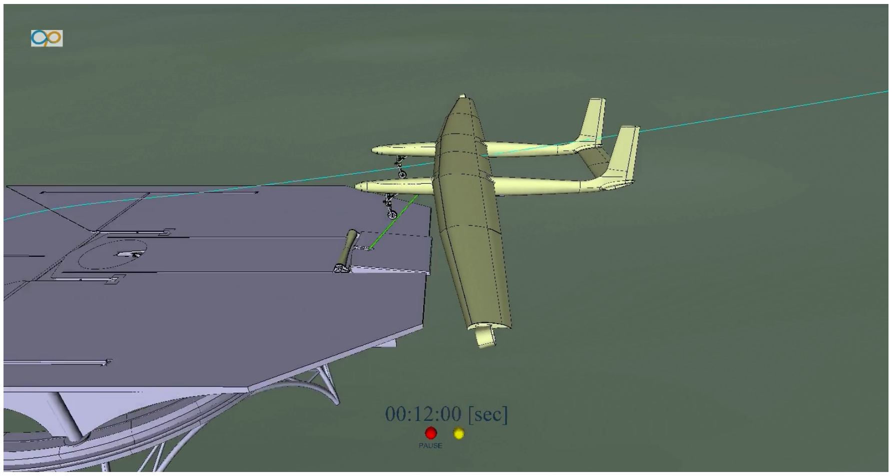


Fig. 26.10 Ampyx Power 6-DOF simulation including environmental and sensor disturbance models for Monte Carlo analysis. Here a tethered landing onto the platform under a gusty 8 Beaufort (17.2 to 20.7 m/s) wind conditions is shown

The resulting power curves from these analyses typically look like the curves shown in Fig. 26.11. Three regimes can be distinguished:

1. Cubic law regime. This is the regime where Loyd's estimation works well, at least as a trend [9]. The power rises with the cube of the wind speed.
2. Linear regime. The maximum cable tension has been reached, and the cable is operated at maximum tension. The reel-rate increases with the wind speed to limit the tension.
3. Flat regime. The maximum reel rate and generator power has been achieved. E.g. through angle of attack control the power is limited. In fact, in this regime, power production will generally decrease somewhat with increasing wind speed, e.g. due to larger margins to be taken for gust loads.

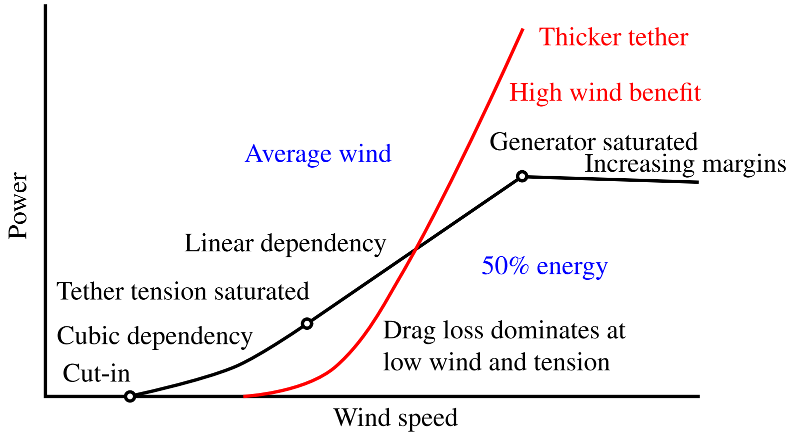


Fig. 26.11 Typical power curves as function for a typical optimal tether and a thicker tether. A tether designed for high tension has large drag losses at medium wind speeds. The typical transition points for an optimal tether selection are indicated. The tether is operated at maximum tension above approx. average wind speed, the power generator is sized (and power curve capped) to the power output achieved at approx. the 50% yearly energy wind level

The lesson learned from this analysis is the impact that the drag of a realistic tether has on performance. With a thin tether, the maximum tension is reached already at low wind speed, and the power gain with higher wind speed becomes linear through most of the regime. It would seem more favorable to have a thicker tether, such that the (seemingly beneficial) cubic growth of power with wind speed is stretched deep into the high-wind regime. However, such a tether has a large drag and at low wind speeds, it is not used to its potential (not fully loaded), and unnecessary tether drag is suffered. The result is that the power curves, though cubic, are so flat initially that the benefit of the thick tether only becomes apparent at very high wind speeds, which in turn are exceedingly rare and contribute little to the yearly energy production [3].

When the power curves are multiplied by the wind statistics distribution (e.g. a Weibull), the optimal tether thickness for a given aircraft design and wind statistics can become clear. It seems that approximately, the optimal tether thickness would lead to transition to the linear regime around the average wind speed [3, Fig. 11].

Primary factors that have a significant impact on power production have been analyzed to be:

- Reel-in speed: increase from 20 to 30 m/s raises power by 10%
- Capping of maximum power to limits of generator: relatively small effect: limiting the maximum power to 50% of the peak level at 20 m/s capping has only 5% effect on yearly power produced. The cost model indicates that the optimum generator is sized to reach full power at about 13 to 15 m/s, a value similar to conventional turbines. Techniques to cap the power include angle of attack / flap angle control, pattern elevation control and pattern width.

- System efficiencies: with respect to the mechanical reel-out power in ideal conditions (point mass), an overall 50 to 60% efficiency is considered a fair target to account for control and power conversion losses.
- Lift of wing profile: can be improved by multi-element wings, flow control etc. A coefficient of $C_L = 2.4$ for the entire vehicle, or higher, seems feasible.
- Roll angle: to fly the steep curves of the pattern, a system with large mass or short tether needs either a large roll angle, a longer tether or a wider pattern. A large roll angle between tether and aircraft body causes unfavorable loading of the tether (power loss), yet a shorter tether means less drag.
- Drag of tether: can be improved by 30% with e.g. latex coating, and by having a thinner cable although it would have to be replaced more often [6], experiences with Dyneema®material in [2]. The tether length is to be minimized, and is determined by the (optimal) roll angle (initial length) and the high wind reel-out (final length).

Figure 26.12 illustrates how our toolset can be used to optimize for a given mass and find the design that provides the best cycle power output. In fact, this is what we have done for AP-3. For AP-3, being primarily an autonomy demonstrator, size is the primary constraint, not LCoE.

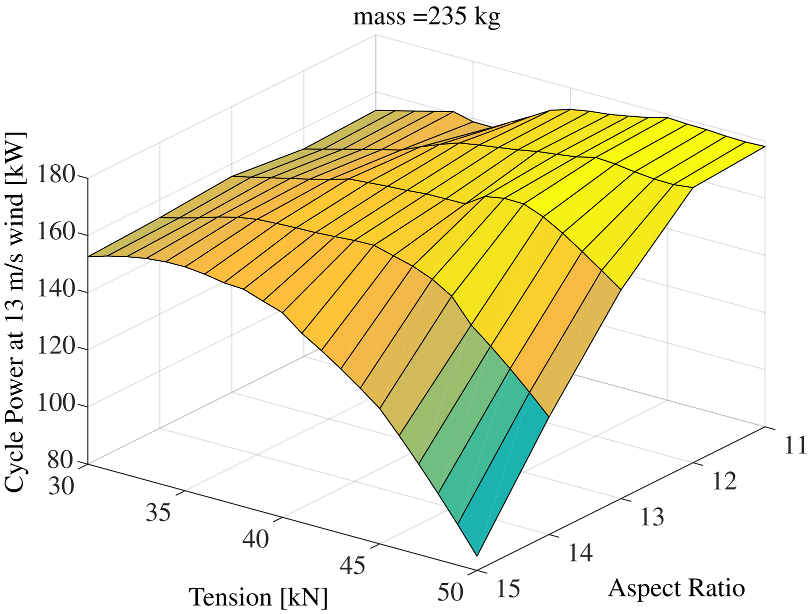
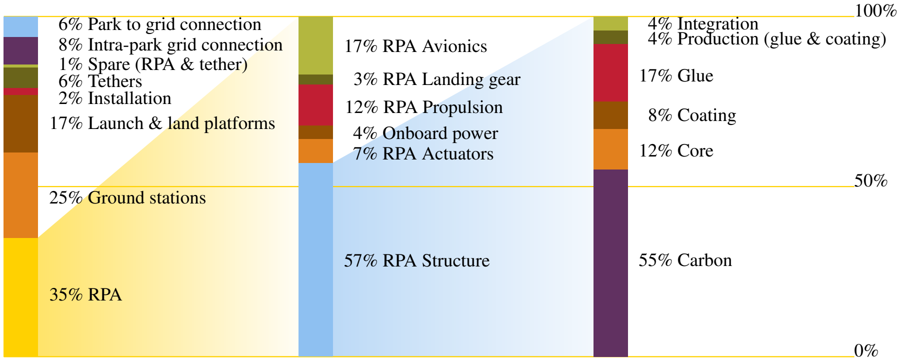


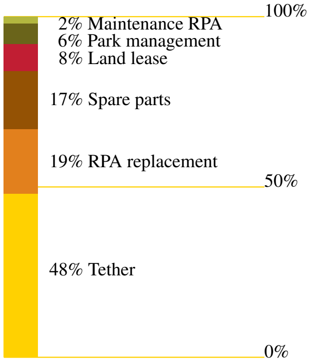
Fig. 26.12 Optimization of cable tension and wing aspect ratio towards maximum power output for a 235 kg aircraft

26.4.3 Cost Model and LCoE

In case of our commercial system AP-4, we are optimizing for minimal LCoE. Our model for LCoE includes a break-down into the known subsystems of the full facility and balance of plant parametric dependencies of cost on system sizing (esp. power output, cable length and cable tension, based on proxies from the wind turbine and aeronautical industry), as well as operational cost and modeled cable wear. Each input parameter has a range that is based on commercial and aviation cost levels. Uncertainty margin on the absolute results for this model and our input parameters is about 0.5 ct/kWh. Some typical results for an AP-4 analysis are provided in Fig. 26.13. Results of our model are roughly confirmed by Chap. 30 in this book.



(a) CAPEX breakdown wind park (b) CAPEX breakdown RPA (c) CAPEX breakdown RPA structure



(d) OPEX breakdown wind park

Fig. 26.13 Cost factors in Ampyx Power commercial sizing exercise and relative contributions

From a sensitivity analysis on LCoE, based on variation of all discussed design parameters, there appears to be an optimal wing area for minimal LCoE, as shown in Fig. 26.14. Best net profit for a given plant area may be obtained for wing areas roughly twice that size.

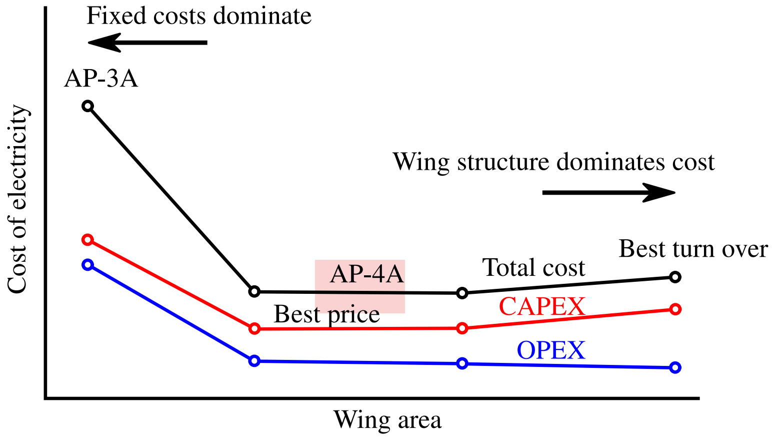


Fig. 26.14 Trends of Ampyx Power commercial sizing exercise and AP-4A target

26.5 Conclusions

The Ampyx Power AWES generates energy by flying a tethered rigid glider-aircraft attached to a ground-based generator. It follows a crosswind pattern as the tether unwinds under high tension and the aircraft spirals away from the generator. The tether rewinds under near-zero tension while the aircraft glides back to the generator. Ampyx Power targets the utility market, including offshore, and therefore requires high power output and high levels of autonomy, safety and reliability. This objective led us to a rotating-platform type horizontal Launch & Land solution. Ampyx Power currently operates 2 prototypes (AP-2A1 and AP-2A2, about 20 kW net power production demonstrated) in a test field in The Netherlands. The AP-3 with 200 kW is currently under development for which we have implemented and customized aeronautical design processes, airworthiness and safety standards. The commercial product AP-4 has been sized for minimal LCoE, resulting in a 2 MW class system. It shall operate at a LCoE well below that of conventional wind energy. The final offshore solution should feature a high power density per square kilometer surface area. The price estimate and system sizing are based on dynamic simulations over a range of wind speeds for typical sites, coupled to an aero/structural model and a cost model including capital and operational aspects. The dynamic simulations have been cross-validated as well as matched against AP-2 flight data. A step-wise development of avionics redundancy has been described, that should eventually allow co-use of the terrain overflown by the tethered aircraft. The presented approach has been developed for a rigid wing utility-scale AWE system, but may be more generally applicable within the wider AWE community.

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