KITING FOR WIND POWER

To access wind at altitudes above 200 meters, the Kite Power Research Group at Delft University in The Netherlands is capturing wind energy with Airborne Wind Energy (AWE), or computer-controlled kites.

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THE MAJOR PART OF ATMOSPHERIC WIND energy is inaccessible to conventional wind turbines. Computer-controlled kites provide an attractive solution to efficiently harvest this resource.

Wind generally gets stronger and more persistent with increasing altitude. For this reason, tower height is an important factor in the design of wind turbines and greatly affects their power output and capacity factor. However, even the largest turbines in the megawatt-range cannot exceed altitudes much beyond 200 meters due to the structural limits of tower-based designs. For offshore and particularly for deep-water deployment of such large turbines, the additional investments in foundations or mooring platforms are decisive cost factors.

HIGH ALTITUDE WIND

Airborne Wind Energy (AWE) systems are designed to operate at higher altitudes. Common features of the many different concepts are flying devices such as wings, aerostats, or hybrid designs, which are tethered to ground stations and which can be controlled in altitude and flight path. Adjusting the operation to the prevailing wind conditions, significantly increased capacity factors can be expected.

Fig 1: A 25 m2 traction kite flying high on a single-line tether.

Several concepts are already tested as prototypes and indicate that the technology is particularly attractive for areas where conventional wind energy systems cannot be operated economically.

AWE systems have other distinct advantages. Replacing the rigid tower of a wind turbine by a lightweight tensile structure directly translates into lower investment costs and a lower environmental footprint. The reduced visual and acoustic impact is an advantage for installations in ecologically sensitive areas or tourist destinations, while the low weight and compact dimensions is particularly suitable for mobile deployment.

TURBINE OR TRACTION POWER?

The existing approaches can be classified by the position of the electrical generator. "Flygen" concepts use either propeller turbines on the flying device or the flow-induced rotational motion of the complete device to drive on-board generators. The electrical energy is transmitted to the ground by a conducting tether. Essential advantages are the continuous generation and the comparatively simple launch and retrieval of the flying device, using the generators as motors to provide thrust and lift for hovering away from and back to the ground station. Technological challenges are the development of lightweight generators with high power density and of conducting flexible tethers capable of withstanding high mechanical loads.

Fundamentally different, "groundgen" concepts are based on the conversion of traction power using cable drums and connected generators on the ground. Essential advantages are the positioning of the heavy system components on the ground and the possible optimization for maximum traction performance and controllability. However, a single flying device requires operation in periodic cycles, alternating between reel-out and reel-in of the tether. As a consequence, electricity generation is intermittent requiring buffering across the cycles. Continuous generation can be achieved by using multiple, individually controlled flying devices to drive a loop configuration.

CONVERTING THE TRACTION POWER OF KITES

One of these designs is the "laddermill". Patented by former ESA astronaut Wubbo Ockels in 1996, it is based on a cable loop, which runs through a pulley at the ground station several kilometers into the sky. Kites are attached to the cable at equidistant intervals and by individually adjusting their aerodynamic properties for high lift in the upward moving section and low lift in the downward moving section of the loop, where a net traction force is established driving the generator connected to the pulley. The aim of the original concept is to access the kinetic energy of high altitude wind, however, it is obvious that a realization of such a large-scale system with many connected airborne components will be an outstanding technical challenge.

Avoiding the complexity of the airborne cable loop, the German company, NTS Nature Technology Systems, is developing a prototype system based on a cable loop, which is integrated into a horizontal rail track for kite buggies.

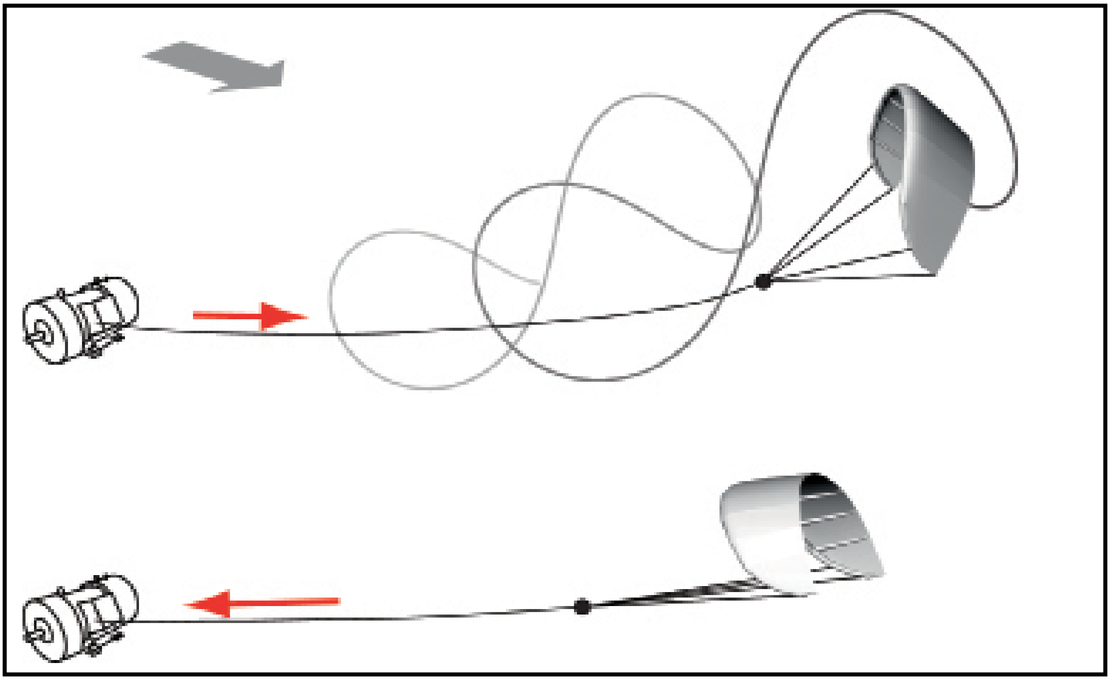


Fig 2: The system is operated in periodic pumping cycles, alternating between reel-out (top) and reel-in (bottom) of the tether.

Fig 3: 25 m2 Leading Edge Inflatable tube kite with suspended, tele-operated control unit.

Most of the current activities are focused on single-kite systems. A prominent example is the kite-based traction system for large cargo ships developed by the German company SkySails. The commercially available system can achieve fuel savings of up to 35% using kites of up to 320 square meters surface area with up to 160 kilonewtons (kN) of traction force. Single-kite systems for energy generation are based on the "ground-gen" concept. To maximize the energy generated in the reel-out phase, the kite is flying fast crosswind maneuvers (see figure 2 top). This substantially increases the aerodynamic forces, lift and drag, which depend on the square of the relative wind velocity that the kite experiences. Typical flight patterns are figure-of-eights or circles, which are both used by kite surfers to achieve high speeds.

In the reel-in phase, the generator is operated as a motor and the kite is pulled back towards the ground station. The angle of

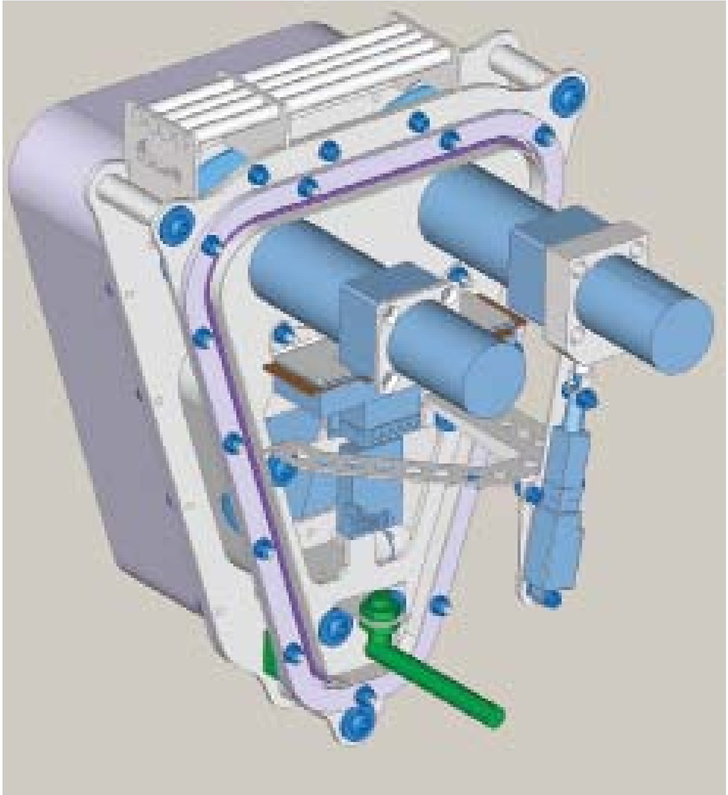


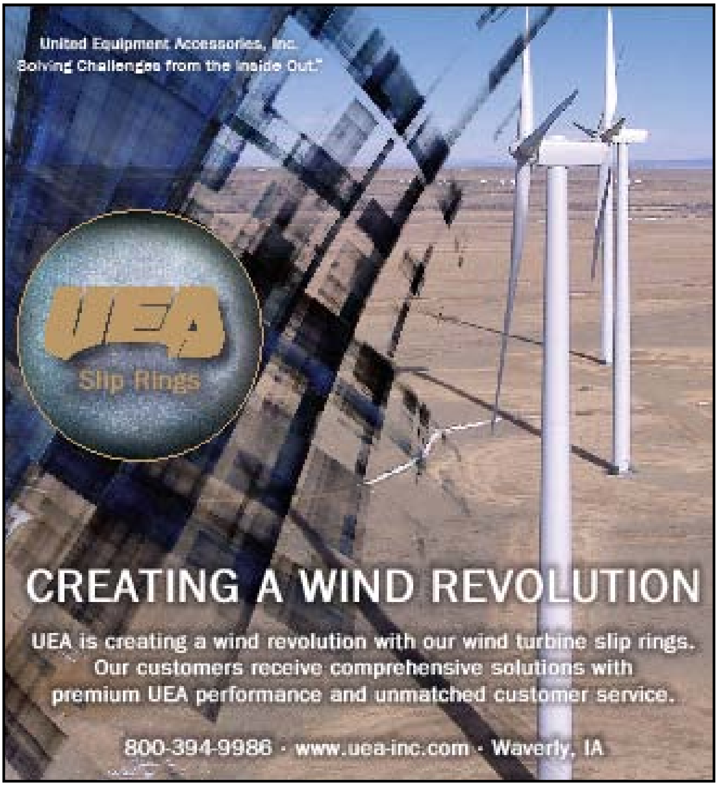
Fig 4: The Kite Control Unit incorporates two powerful micro-winches for steering and de-powering of the wing.

attack of the wing is decreased by rotating the kite into the relative wind to reduce the traction force (see figure 2 bottom). As a result of this de-power manuever, the reel-in of the tether requires only a small fraction of the energy generated during reel-out.

Balancing the energy across the periodic pumping cycles requires a storage mechanism, which can be an integrated battery module or a mechanical flywheel module. For a group of interconnected systems buffer capacity is less of an issue as the systems can be operated with phase-shifted pumping cycles. The Kite Power Research Group of Delft University of Technology initially tested a first experimental prototype of 3 kilowatts (kW) traction power in 2007 and since January 2010 a 20 kW prototype. The developments are co-financed with one million Euros by the Rotterdam Climate Initiative (RCI) and with 136,000 Euros by the Dutch province Friesland.

THE 20 KW KITE POWER SYSTEM

To minimize aerodynamic drag, a single cable is used to tether the Kite Control Unit (KCU), which is suspended some 10 meters below the kite wing (see figure 3), to the ground station. The cable is made of the high-strength plastic fiber, Dyneema. It has a diameter of 4 millimeters and a total length of 1 kilometer with the option to extend to 10 kilometers. A custom-made, Leading Edge Inflatable (LEI) tube kite with a surface area of 25 square meters generates the traction force. The main components of this inflatable membrane wing are the front tube, defining the curvature of the wing, the connected strut tubes, defining the



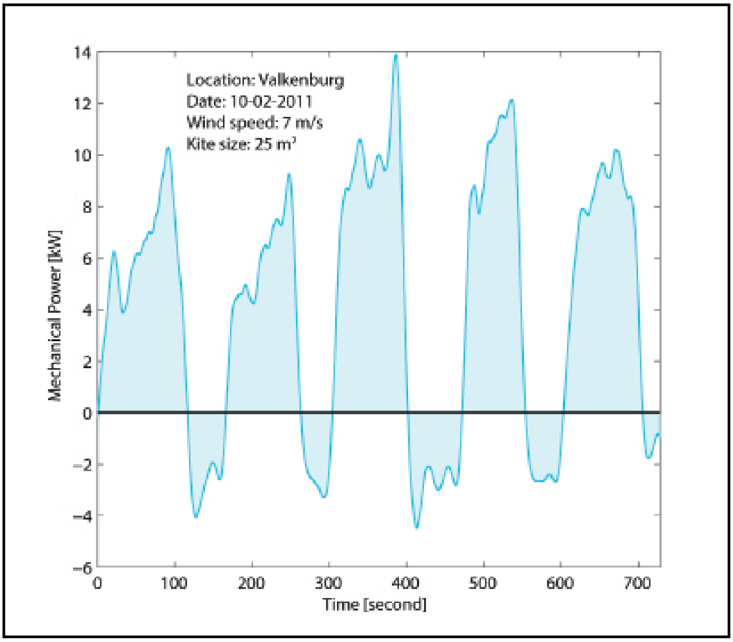


Fig 5: Traction power over five consecutive pumping cycles: reel-out phases (P > 0) and reel-in phases.

wing profile, and the canopy. The bridle line system connects the front tube to the structural frame of the KCU. The design of the bridle system incorporates pulleys to allow for deformation of the curved wing when rotating during a de-power manuever.

The KCU essentially is a cable robot incorporating two small but strong motor-winches for steering and de-powering of the wing using the two steering lines attached to the rear ends of the wing tips (see figure 3). It is connected to the ground station by two redundant wireless links. The autopilot software runs on the ground station computer and uses data transmitted from the KCU–the control positions and status of the different actuators–and from two sensor units mounted on the kite. The software alternates between two control modes corresponding to the two phases of the pumping cycle: a figure-of-eight trajectory control during reel-out, and symmetry plane stabilization during reel-in. The system tests in December 2011 have confirmed the reliability of the autopilot approach.

The ground station incorporates the generator with a rated power of 20 kW and a connected drum. Both are mounted on a sled, which is part of the feeding mechanism for the tether (see figure 4). A rechargeable battery module with a capacity of 18 kilowatt-hours allows for stand-alone operation and to cover periods of low wind by keeping the system employing reverse pumping cycles. The ground station controller uses measured velocity and force data to adapt the rotational speed of the drum such that the forces stay within the limitations of the system. An important feature of the development platform is the logging of all measurement data together with the video streams of various cameras at the ground station, the kite and the kite control unit. This data is used to analyse and improve the flight dynamics and structural dynamics of the kite as well as the performance of the complete kite power system.

OPERATION AND TEST RESULTS

More than 400 pumping cycles (equivalent to 13 hours continuous operation)” have been recorded and analysed in detail. The maximum operational altitude depends mainly on local airspace regulations. At the present test site, the former naval airbase of Valkenburg, which is located in the controlled airspace of the international airport Amsterdam, the operational altitude varies between 150 and 300 m, with the length of the cable varying between 180 and 400 m. At a more remote test site, a maximum height of 500 m with a maximum cable length of 700 m was possible. Depending on the wind velocity, the flight velocity of the kite during reel-out is between 70 and 90 kilometres per hour. To maximise the net energy per pumping cycle, the reel-in phase has to be as short as possible with the tension in the cable as low as possible. However, de-powering the kite by rotating it into the relative wind negatively affects the flight stability and steering behaviour and in practice, a compromise between achievable de-power and diminished flight authority is required. For operation at a wind speed of 7 m/s, the cable force can effectively be lowered from 3.1 kN during reel-out to 0.6 kN during reel-in at a speed of 5 m/s.

The figure 5 shows the instantaneous traction power at the drum over 5 consecutive pumping cycles, illustrating the alternating energy generation and consumption phases. The oscillations during reel-out are caused by the variation of the relative wind velocity during the figure-of-eight flight manoeuvres, between 4 and 5 per reel-out phase in this particular test. Considering the complete cycle, the traction power average is 4 kW. As a result of systematic optimizations on component- and system-level, affecting the kite

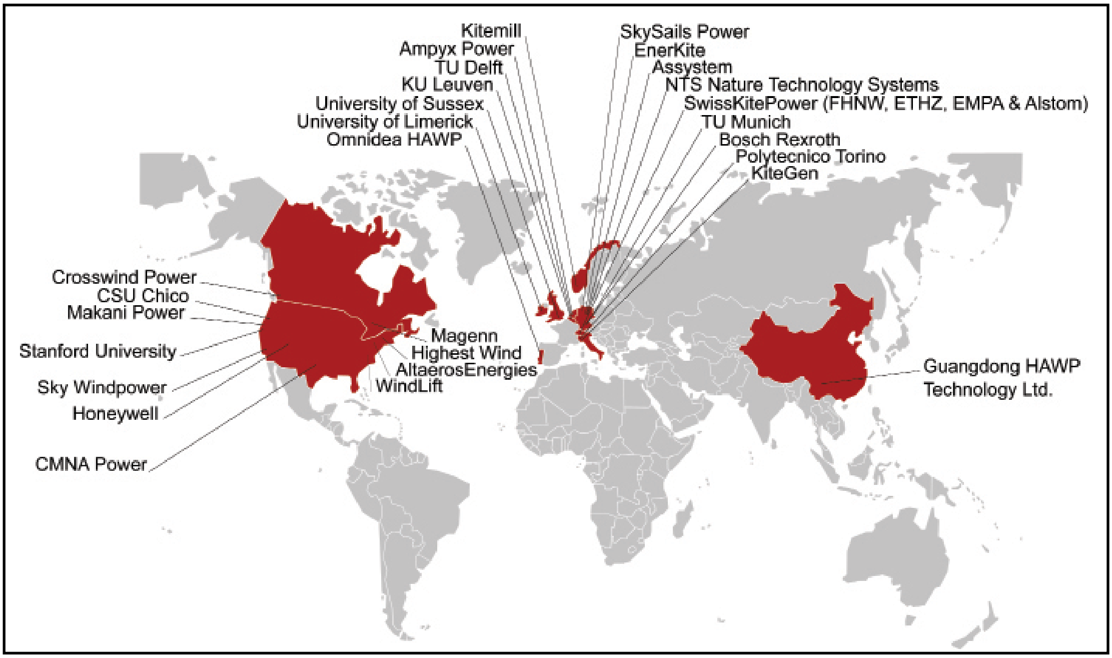


Fig 6: International research and development activities on Airborne Wind Energy in 2012.

and bridle system design, the responsiveness of the ground station winch and the flight trajectory, the traction power average has been increased to presently 6.5 kW, with the goal to achieve 9.6 kW in the near future. The tests have shown that the kite energy system can be operated even with very little wind on the ground. In this case, the kite is winch-launched, like a glider

Fig 7: Cable drum and 20 kW electrical generator.

plane, until it picks up the wind at higher altitudes. The current system can be operated at wind velocities up to 9 m/s, resulting in a projected aerodynamic wing loading up to 30 kg/m2. For stronger wind a smaller kite can be used up to the maximum wing loading of 40 to 50 kg/m2 for kite designs based on Nylon.

FUTURE APPLICATION AREAS

The specific design of kite power systems is attractive for a number of application areas. With a rated power between 10 and 30 kW, commercial derivatives of the technology demonstrator system are suited for distributed generation of renewable energy in remote areas or in disaster areas, especially when deployment and start-up times are crucial and fuel supply is cost-decisive. For stand-alone systems of this power range, full automation is not strictly required and, consequently, ground personnel can assist launch and retrieval of the kite. Once in the air, the kite control unit and ground station winch switch to automatic operation. The production cost of a small-scale power system will be determined mainly by the ground station and the kite control unit, both incorporating mechatronic components with various sensors and embedded control systems. The flexible airborne system components – kite, bridle system and tether – are optimized to capture and transfer the aerodynamic force to the ground. Compared to the costs for structure and foundation of equivalent wind turbines, these components are inexpensive. Due to material degradation, a replacement in periodic intervals will be required, which will affect the operational costs of the system.

Offshore wind energy could profit in a major way from the cost advantage of kite power systems. Since the generator is close to the sea level, the moment induced by the traction force of the kite is a tiny fraction of the moment induced by a wind turbine tower rising to more than 100 m above sea level. For this reason, kite power systems can be deployed from inexpensive floating platforms, which are moored to the seabed to avoid drifting. The technology of semi-automated launch and retrieval of kites with surface areas of several hundred square metres from ships has been successfully developed and commercialized by SkySails. This demonstrates that large-scale offshore deployment of kite power systems in the MW-range is technically feasible. The environmental impact of an offshore wind park of kite power systems will be lower than that of a conventional wind farm. The cables leading into the sky are hardly perceivable from a distance and the same holds for the large membrane wings sweeping back and forth at higher altitudes. As consequence, the new technology has the potential to significantly alter the public perception of wind power and thus accelerate the transition from fossil and nuclear energy to renewable energy.

CURRENT R&D LANDSCAPE OF AWE TECHNOLOGIES

A key challenge for current research and development activities is robust automatic operation of tethered flying devices, which is a central requirement for reliable base load power generation. Recent advances in flight control algorithms, modelling of structural dynamics, aerodynamics and flight dynamics of flexible membrane wings, and the availability of hardware prototypes with sensor equipment have led to several successful demonstrations of automated flight. Similarly important are technological advances on high-strength, lightweight and UV-resistant materials to significantly increase the durability and lifetime of the airborne system components and thus decrease the maintenance effort and operational costs of AWE systems.

The emergence of AWE as a new technology complementary

Fig 8: A 25 m2 tube kite flying cross wind maneuvers observed from the ground station.

to conventional wind energy is relatively recent, mainly motivated by the drastically increased demand for renewable energy. For example, the number of institutions actively involved in AWE has increased from three in 2000 to presently over 40 (see figure 6). The last 5 years have also seen some major investments. Since 2006, Google has invested $15 million in California-based start-up company Makani. In 2010, the company received an additional ARPA-E grant of $3 million from the U.S. government and it recently won the Popular Mechanic's 2011 Breakthrough Innovator Award in the Energy Category.

In 2011 the high altitude wind power group of the University of Leuven in Belgium received an ERC Starting Grant of one million Euros from the European Union.

The annual event for presentation of research and development achievements, exchange of ideas and development of new visions is the Airborne Wind Energy Conference (AWEC). After the successful launch in 2010 at Stanford University, in California, the event was held in May 2011 in Leuven, Belgium. Mid 2011, SkySails announced use of their technology base of kite-assisted ship traction as a starting point for venturing into power generation. Coincidentally, Garrad Hassan, a globally operating wind energy-consulting firm, has published a market status report on high altitude wind energy, critically analyzing more than 20 of the most advanced AWE projects.

Business research and consulting firm Frost & Sullivan, and the German Fraunhofer Institute are preparing technology assessment reports.