Airborne Wind Energy Systems

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Because of the near-term risk of extreme weather events and other adverse consequences from climate change and, at least in the longer term, global fossil fuel depletion, there is worldwide interest in shifting to noncarbon energy sources, especially renewable energy (RE). Because of possible limitations on conventional renewable energy sources, researchers have looked for ways of overcoming these shortcomings by introducing radically new energy technologies. For wind energy, a possible alternative is airborne wind turbines.

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Several major problems hinder conventional wind power development. In many regions, average wind speeds are too low to give an adequate energy return on energy invested (EROI) for wind farms erected there. Even if average wind speeds are sufficient to give an adequate EROI, the wind is variable, with periods of low to zero output. Land-based wind farms also face a number of environmental problems, including bat and bird collisions with turbines, and opposition from nearby residents because of perceived visual obtrusion on the landscape or turbine noise and vibration. One solution is to move windfarms offshore, and an increasing number of these are being constructed, particularly in the North Sea off Europe.

A more radical solution to these problems is to make the wind turbines airborne. Marvel et al. [1] found that a global potential of 400 terawatt (TW = 1012 watt) was available from ground-based turbines, but vastly more (1800 TW) from airborne devices, compared with about 18 TW of global primary power consumption from all energy sources today. They concluded that human extraction of wind energy would have little effect on Earth’s climate. Research on Airborne Wind Energy Systems (AWESs) started in the 1970s was almost abandoned in the 1990s but has seen rapid growth in recent years [2].

Wind turbines constructed close to the ground encounter a variable vertical wind profile and lower wind speeds compared with higher altitudes [3]. Winds are also less intermittent at high altitudes. Other possible advantages are that towers and heavy foundations necessary for ground-based turbines can be dispensed with. Further, maintenance can be done on the ground, as all designs are tethered and can be winched back to the surface. The ground stations themselves can be fixed or can even move in pre-determined, coordinated patterns. For example, the ground stations, each connected to an AWES, could move along a closed-loop or open-loop rail line [3].

Three basic types of AWESs have been considered, a large variety of prototypes have been designed and tested [4][5][6] and hundreds of patents have been granted. A review by Watson et al. [2] contains a full classification and description of the various approaches possible for AWESs but warned that “convergence towards the best architecture has not yet been achieved.” (Given the risk these may pose, the emphasis is on engineering design in patents for AWESs, in contrast to the other two new, more science-based, technologies discussed in this paper.) Hence, unlike ground-based wind turbines, no standardized designs are on the horizon, which makes any possible large-scale implementation decades away. The simplest AWES is to fix one or more turbines to a large helium balloon. This approach is restricted to relatively low altitudes (around 200–600 m), because at higher altitudes not only must the size of the blimp increase for a fixed payload, but blimps also encounter higher wind speeds and so considerable drag [7]. Similar to all AWESs, the blimp must be tethered to a winch on the ground by a strong cable, which (except for kite designs) must also be able to conduct electric power from the turbines. For all airborne types, high tech materials with a high tensile strength to weight ratio will be needed to reduce the weight of the tethers, which could be up to several kilometres long. Tethered balloons are already used for other purposes, so the technology is well established, as are aviation laws governing their safe use, although the prospect of a live tethered cable could require additional regulation.

A second approach to AWESs employs a tethered “aircraft” (or rotorcraft) with one or more wind turbines to generate electricity on-board, then transmit this to a fixed or moveable ground station. The aircraft produce electric power except when taking off and landing, when they are net power consumers. For all AWESs, there is a conflict between the higher wind speeds available at greater altitudes, and safety and cable drag considerations, which favor lower altitudes. A paper by Roberts et al. [8] has discussed one such approach: “At 15,000 ft (4600 m) and above, tethered rotorcraft, with four or more rotors mounted on each unit, could give individual rated outputs of up to 40 MW. These aircrafts would be highly controllable and could be flown in arrays, making them a large-scale source of reliable wind power”.

The technology that departs most from conventional turbines would employ kites to generate energy. The tethered kite (an air foil) is connected to a ground-based generator with two cables. When the kite is released into the air, tension in one cable as the kite ascends can be used to drive a generator. In the second phase, the kite is reeled in, using the generator as a motor; the angle of attack of the kite is reduced, thus lowering line tension. The energy generated during the “reel out” part of the cycle exceeds the energy needed for the “reel in” part [4][6]. Unlike other AWES designs, no power cable is needed, but sophisticated control systems are essential. Arrays of these could operate in pairs to achieve stable supply over the two phases of operation.

Lunney et al. [5] examined the feasibility, potential and costs of air borne turbines in a Northern Irish context. They found that at a fixed altitude of 3000 m, turbines could be flown over 5110 km2 of the region, which has a total area of 14,130 km2 and lies roughly between 54–55° North. These authors attempted an initial cost estimate for a 2 MW “pumping” kite device. They calculated a total cost GBP 1.75 million, or GBP 0.875 million for each MW, which cost they regarded as comparable with conventional wind turbines. At 2016 exchange rates and prices, this comes to USD 1.34 million per MW.

Costs were also estimated in the paper by Roberts et al. The costs were for a 100 MW array, consisting of individual 3.4 MW output “flying electrical generators”, each weighing 9.5 ton. Including ground base costs, each 3.4 MW unit was estimated to cost USD 2.26 million, assuming production rates of 250 per year. Including balance-of-system costs brought total costs for 100 MW to USD 71.2 million, or USD 0.712 million per one MW, presumably in 2006 money values. Expressed in 2016 values [9], a value of around USD 0.85 million per MW is obtained, less than the estimated unit cost of the Northern Irish pumping kite. The difference may be due to the Roberts et al. paper assuming volume production of the units. Estimated costs for conventional wind turbines in 2016 were somewhat higher [10] but included several cost items missing from the AWES analyses.

In the Roberts et al. paper, an energy analysis was also performed for three possible sites in the US. For the best site, above Topeka, Kansas, in the Great Plains, a capacity factor of 91% was calculated. Although downtime for storms, maintenance, etc., would reduce capacity factors, they should still be far higher than conventional ground turbines, with a capacity factor of typically around 30% or less. For an EROI calculation, input and operating energy costs are needed as well as output energy, but these were not calculated. For a conventional turbine with 3.0 MW rated output, Crawford [11] has estimated that tower and foundation materials only accounted for around 25% of total embodied energy. AWES would not need a tower, and the heavy foundation could be replaced by a lighter cable anchor, but energy costs of the cable, ground station and far longer road and transmission network would more than neutralize these savings. Until such AWESs are operational, their EROI must remain speculative.

Safety is a key consideration for airborne modules. For both safety and environmental reasons in the Lunney et al. analysis, areas above, for example, towns and cities, transport corridors and nature reserves, were excluded. Air transport corridors and airports represent a special hazard, as airborne device heights will overlap with aircraft heights. Power lines are another obvious hazard; lightning strikes will also pose a potential risk. During storms it may be necessary to reel the AWESs back to ground. Clearly, at a minimum, the maximum tether length provides the radius for exclusion zones for each AWES. Within each airborne wind farm the minimum device spacing is also the maximum tether length. Depending on length and materials used, the tethers themselves could weigh several tons.

For commercial success, the new technologies have to prove themselves as superior in important respects (such as costs or efficiency) to the conventional RE technologies they hope to displace, or at least complement. The review of AWESs discussed here has shown that this is far from the case for this new technology.

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