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Energy High in the Sky
EXPERT PERSPECTIVES on Airborne Wind Energy Systems

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Executive Summary

Winds near Earth's surface are already used to generate substantial amounts of electricity. However, higher in the sky—much higher than today's wind turbines can reach—winds tend to be stronger and steadier, making these winds an even larger source of energy. Various companies have formed that aim to capture energy in these high-altitude winds using aircraft tethered to the ground. To scale up, these aircraft must be able to produce electricity cheaply enough and reliably enough to compete in electricity markets.

About two dozen research groups—at companies, universities, and government labs including NASA—have been studying ways of capturing energy from these high-altitude winds. These approaches are generally known as "airborne wind energy," and while diverse, they all involve a flying component that harnesses the wind energy—in some cases kites, airfoils, blimp-like balloons, and wings or planes. In each case, the aircraft is held in place by a tether that ties them to a particular locale, while also transmitting energy from high-altitudes down to the ground. The amount of energy that can potentially be extracted from high-altitude winds is enormous, but the field of airborne wind energy is still in its infancy, according to an independent report by renewable energy consultants GL Garrad Hassan.

Near Zero conducted both an informal discussion and a formal survey to find out what technologies are most advanced, which have the best potential, and how best government could jumpstart the development of the airborne wind energy industry. Thirty-one experts completed the formal survey, identifying technological, engineering, and regulatory barriers to testing airborne wind energy technologies and bringing the industry to large scale.

The results suggest that the airborne wind energy could grow quickly, as long as it gets a jump-start with government funding for R&D. During this initial stage of the industry's development, funding of $10 million per year could cut many years off how long it takes for the industry to reach a significant scale, and funding of $100 million per year would further accelerate the deployment of high-altitude wind generators, the experts said.

Although there are many technological and engineering barriers, most of the experts agreed that one of the biggest barriers is the body of existing regulations, which pose a challenge both for testing prototypes today and for large-scale implementation in coming years. These regulations include limits on what kinds of aircraft can fly and where, and also requirements for permits and safety systems. Thus regulations pose a challenge for rapid testing of various prototypes, a process experts said is necessary for working out which technologies are most promising, and to allow them to cross the "valley of death" from prototype stage to commercial stage.

The experts argued in favor of spending a larger share of research funds on systems that show greater promise of being able to scale up to large systems. They favored particular types of systems—those using rigid wings—and argued against funding those using balloons. Some experts also suggested installing airborne wind energy systems offshore, in part because of the large wind resource available, and because regulatory and safety issues may be easier to resolve than for land-based systems.

A Vast Resource at Great Heights

Near Zero's survey asked 31 experts a series of quantitative questions about which approaches they felt deserved the most funding, what some of the main barriers are, and how best to overcome these barriers. The researchers came from a variety of backgrounds—from engineering to finance—and many are involved in research on airborne wind technologies, or in businesses building these technologies. While experts surveyed by Near Zero may not be representative of all wind energy experts, the results shed light on the burgeoning field of airborne wind energy, and suggest ways forward to help get the industry off the ground.

It is well established that winds become more intense at greater heights above Earth's surface[1] —a major reason why wind turbines have been hoisted onto ever-taller towers, the tallest about 160 meters (530 feet), with blades that reach up to about 230 meters (770 feet). But there are limits to how high these turbine towers can practically reach, and building taller towers would likely increase the cost of wind power, both as measured in dollars and energy consumed in building wind farms.

Up higher than traditional winds turbines can reach are more powerful winds, which require new strategies to harness—strategies that more than two dozen companies and research groups are now exploring. Although the approaches are varied, they all share one common characteristic: They dispense with traditional wind turbines and their towers, and instead feature an airborne component—such as a kite, wing, or balloon—that captures energy in the wind. Because of these commonalities, the various technologies are all referred to as "airborne wind energy." The aircraft is tied to a particular spot on the ground by a long tether, which also serves to transmit wind energy to the ground.

There are a variety of technologies and approaches that have been devised so far, some tailored for small-scale systems for remote areas and developing countries, some aimed at becoming large-scale wind farms that can supplant fossil fuels in creating base-load electricity for energy-hungry cities of industrialized nations.

Two new studies suggest that high-altitude winds are a vast energy resource, at least as large as surface winds.[2][3] One of the studies, by researchers at Lawrence Livermore National Lab and the Carnegie Institution of Washington estimates that just the jet streams—fast-flowing, high-altitude winds—carry 100 times as much power as humanity now uses.

Since high-altitude winds are generally stronger, it means that more energy is available to harness in a particular location. And since high-altitude winds generally blow more consistently than low-altitude winds, airborne wind systems may be more attractive than traditional wind turbines. Overall, compared with traditional wind power, airborne wind energy may be able to provide more electricity, in more locations around the world, and more consistently, and so may be more suitable for replacing fossil fuels for base-load power.

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[1] Arya, S. *Introduction to Micrometeorology* (New York: Academic Press, 1988), p. 303

[2] Marvel, K., B. Kravitz and K. Caldeira, "Geophysical Limits to Global Wind Power," *Nature Climate Change* (2012), in press.

[3] Jacobsen, M. and C. Archer, "Saturation wind power potential and its implications for wind energy," *Proc Natl Acad Sci* (2012), in press.

Different Heights, Different Markets, Different Strategies

The different approaches can generally be divided into three groups, based on the type of airborne device they use to harness wind energy. One type has rigid wings, as airplanes have—and some of these approaches actually use small airplanes. Another type uses kites, either individual kites or a series of them along a string. A third type uses a lighter-than-air craft like a balloon or blimp to stay aloft.

The approaches also differ in how they turn wind energy into electricity. One method features small wind turbines driving electric generators, all on-board the aircraft. One company taking this approach is California-based Makani Power, employing an aircraft similar to an airplane, with several propellers that serve as wind turbines, and flying at altitudes up to 600 meters.[4] Google has invested $15 million in Makani, and in 2010 the company also received a $3 million grant from the Department of Energy's Advanced Research Projects Agency-Energy (ARPA-E). Massachusetts-based Altaeros also uses flying generators, but instead with balloons. One design tested in spring 2012 uses a donut-shaped blimp holds a wind turbine in the hole in the middle of the donut. In Makani's and Altaeros' devices, as with all approaches using airborne generators, the electricity is transmitted down the tether to the ground.

Another approach transmits the wind energy mechanically down the tether, driving a generator on the ground. The most popular approach of this kind uses a kite—often a rectangular kite, similar to those used in kite surfing—that operates like a yo-yo. The kite flies higher and pulls out a length of tether, which spins an electric generator, and then the kite is winched back toward Earth—and it repeats this cycle over and over. SkySails Power, based in Germany, has already installed such kites on cargo ships so they can be pulled partly by wind and save on fuel. The company is now aiming to build offshore wind farms to generate electricity. Two Italian companies—KiteGen and KITEnrg—are using a similar approach, but based on land. Some proposals also involve hybrid systems, such as a combination of kites and balloons known as "kytoons."

Wind intensity increases up to an altitude of 500 meters above sea-level, then remains roughly constant from 500 meters to 2 kilometers. Above 2 kilometers, the winds increase until they reach maximum intensity around 8 to 10 km (26,000 to 33,000 feet)—just below commercial jets' typical cruising altitude. As with surface winds, high-altitude winds are not evenly distributed around the planet. Some hotspots for high-altitude wind are eastern North America, North Africa and the Arabian Peninsula, China's coast, southern South America, and much of Australia. Some major cities have strong high-altitude winds overhead, including New York City, Tokyo, and Seoul.[5]

In general, going to greater heights would make the devices more expensive, because the tether would grow longer, and the aircraft would have to provide more lift in order to balance the heavier weight of the tether. For the near-term, most systems are aimed at reaching up to about 500 meters, but not much higher. In the longer term, some airborne wind supporters hope to reach altitudes above 2 kilometers. Beyond that altitude, as New York University pysicist Martin Hoffert said in the Near Zero discussion, "you have to climb very high for much less reward."

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[4] Makani Power FAQ, accessed 2012-07-26: http://www.makanipower.com/faq/

[5] Archer, C. and K. Caldeira, "Global Assessment of High-Altitude Wind Power," *Energies*, (2009), v. 2, p. 307-319.

Elicitation Results

Rigid Wings Favored

When asked how to allocate R&D funds across the various competing technologies, overall results argued for a mix of investment, and individual responses from nearly all the experts favored funding a mix of approaches—but nonetheless a clear favorite emerged (see **Fig. 1**). Whether the hypothetical annual fund was $10 million or $100 million, on average the experts allocated half the funding to rigid-wing aircraft. The next most popular option, receiving about a quarter of the funding, was soft-wing aircraft (including kites).

Balloons were the least popular option, with only a handful of experts voting for significant funding for them. The experts were also given the choice of "other," and on average this option received more than twice as much funding as balloons did, highlighting the unpopularity of the balloon option. In the pre-survey discussion, several experts highlighted problems with balloons: Although balloon systems would be simpler in many ways, they would likely produce less power for their size and cost, several experts argued in the pre-survey discussion. For example, mechanical engineer Robert Wilson of Oregon State University argued, "Balloon systems are not worth the money to document their problems."

Two experts highlighted another option, known as autogyros: They feature horizontal blades, similar to helicopters, but the blades are driven by air passing by the blades, driving the blades to spin and provide lift. In these devices, the lift and power generation come from a single device. Martin Hoffert argued that autogyros "are a good bet." Dimitri Chernyshov of Highest Wind, a company pursuing autogyros, likewise argued this approach "will be extremely cost effective at providing continuous power levels below 100 kW [small-scale systems]," but he added that he doesn't "want to even start messing with the forces involved to produce more energy than that." Nonetheless, the company Sky Windpower is attempting to build autogyros for very high altitude winds at several kilometers.

No Agreement on Flying vs. Ground Generators

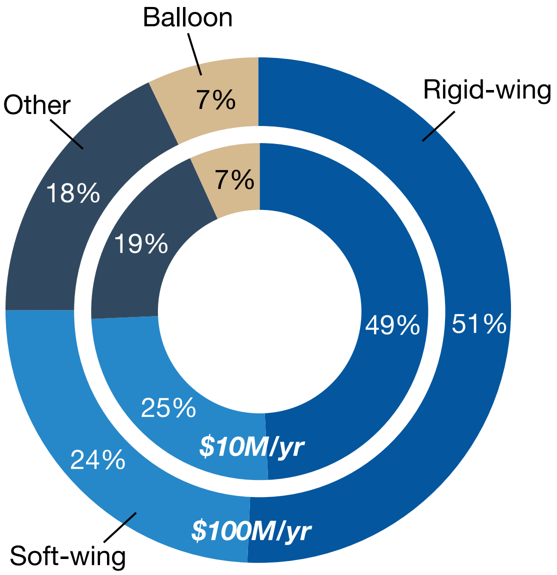

Figure 1 | Types of airborne wind energy aircraft. The experts surveyed clearly favored spending a larger share of funding on rigid-wing aircraft, regardless of the size of the budget available..

When asked about how the government might allocate funds between flying electricity generators and ground-based generators, the answers spanned the widest possible spectrum. The average answer was to split funding evenly between ground-generation and flying-generation—but underlying this average answer was wide disagreement among the experts. In light of this lack of agreement, the results suggest it may be worthwhile to support both basic approaches in the near-term, until tests provide more data to suggest which approach performs better, or which applications each approach is best suited to.

Some of the approaches may be best suited to small-scale systems—such as those that might be easiest to test in the near term, and that in the longer-term might be most appropriate for areas with limited access to electricity, such as remote locations and developing countries. Other approaches may be more suited to scaling up to form large airborne wind farms.

Large-scale Systems Favored

To gauge how much funding should go to small-scale versus large-scale approaches, Near Zero's survey asked experts to divide a hypothetical fund between these two choices. On average, the experts divided a $10 million annual fund evenly, with about half the money going to small-scale systems, and half to large-scale (See **Fig. 2**). There was significant disagreement on the allocation, however, with several experts arguing the vast majority of funds should go to small-scale systems, and several other experts strongly favoring large-scale systems (See **Fig. A2** in the Appendix).

With a $100 million annual fund on the table, the priorities shifted somewhat, and the experts came into greater agreement. In this case, the average answer from the experts was that two-thirds of the money should go toward large-scale systems. Based on the pre-survey discussion, some of the experts involved are interested in niche applications such as providing power to off-grid areas and in emergency relief after disasters, but most of the experts were interested in creating systems that could eventually scale up to provide large gigawatts or even terawatts of electricity, to displace a significant amount of fossil fuel use.

Small-scale may be suitable for particular markets, some experts pointed out. For example, Rob Creighton, CEO of Windlift,[6] argued: "Fabric systems [such as kites] will not scale well to grid scale electricity, and are best suited for small off-grid applications in remote areas," where they could compete with small diesel generators. Kites could likewise "have an immediate impact on the developing world, reducing their growth in carbon emissions and providing economic opportunity," Creighton added.

In the pre-survey discussion, Eric Blumer of Honeywell Aerospace agreed. For smaller-scale systems, around 100 kilowatts, he argued "the balloon and autogyro solutions are probably preferred." But for

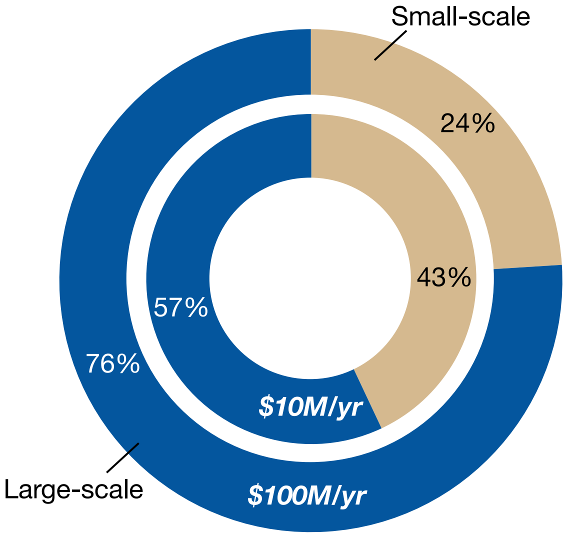

Figure 2 | Large-scale vs. small scale systems. For an annual budget of $10 million per year (inner ring), surveyed experts divided the budget nearly equally between large-scale and small-scale systems. But with higher funding of $100 million per year (outer ring), their preference for large-scale systems increased dramatically.

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[6] U.S.-based Windlift is pursuing small systems with single kites and ground based generators, driven by the "yo-yo" approach. In 2009 they received a contract from the Department of Defense to design a proof-of-concept device.

large-scale wind farms, greater than 1 megawatt, he said, “I believe the fixed wing solution is the most efficient, economical and certifiable” platform.

Onshore vs. Offshore

Although Near Zero’s formal elicitation did not ask about on-shore versus off-shore installation of systems, some experts raised this distinction in the discussion. “I think that offshore [airborne wind energy] is very promising,” said Luciano Fagiano of Italy-based Skymill, “however it’s surely not viable for small scale plants.” This agrees with the assessment of renewable energy consultancy Garrad Hassan, which published in 2011 the first market report on high-altitude wind energy. Their conclusion was “high altitude systems seem promising in terms of offshore application as they could overcome some of the currently challenging hurdles.”[7]

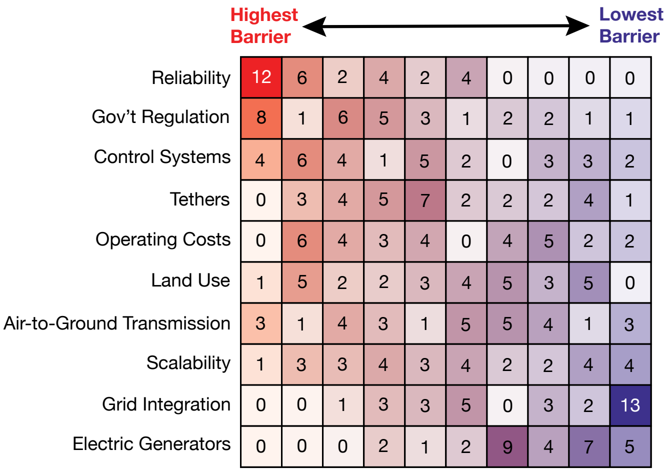
Facing Barriers

Every approach to airborne wind energy is technically challenging, requiring systems that can steer themselves through shifting winds and challenging weather, and that do not require much maintenance or repair so they can remain in flight continuously for months or years. To be economical and also practical to implement on large scales, the aircraft also need to operate largely autonomously, without needing people to constantly steer or otherwise control the aircraft.

Near Zero asked experts to rank 10 different barriers, from the biggest challenge to the smallest challenge (see **Fig. 3**).

The most significant barrier, according to Near Zero’s survey, was reliability. Airborne wind energy aircraft would need to remain in flight most of the time so that they can harvest as much energy as possible. This would require them to be resilient, and need little maintenance or repair. In the pre-survey discussion, experts also highlighted that reliability is also crucial for other components of an airborne wind energy system, such as the tethers and electrical generators. Reliability is a major challenge because building systems to be more reliable and robust may often increase their weight and/or cost.

The second-highest barrier was government regulation. In the U.S., for example, the Federal Aviation Administration (FAA) has strict rules for different classes of aircraft, limiting where they can fly, at what elevations, and what kinds of safety measures they must include (such as flags and lights on the aircraft and tether). In December 2011, the FAA issued proposed rules for airborne wind en-



Reliability	12	6	2	4	2	4	0	0	0	0
Gov’t Regulation	8	1	6	5	3	1	2	2	1	1
Control Systems	4	6	4	1	5	2	0	3	3	2
Tethers	0	3	4	5	7	2	2	2	4	1
Operating Costs	0	6	4	3	4	0	4	5	2	2
Land Use	1	5	2	2	3	4	5	3	5	0
Air-to-Ground Transmission	3	1	4	3	1	5	5	4	1	3
Scalability	1	3	3	4	3	4	2	2	4	4
Grid Integration	0	0	1	3	3	5	0	3	2	13
Electric Generators	0	0	0	2	1	2	9	4	7	5

Figure 3 | Ranking Barriers. Experts ranked barriers to the development of airborne wind energy. To the left of the grid, the options are in order of average ranking, with the highest barriers—reliability of systems and government regulation—at the top of the list. The grid shows the number of votes for each option, at each particular ranking (so 12 experts ranked reliability the highest barrier, and 6 experts ranked it the second-highest barrier).

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[7] GL Garrad Hassan, “Market Report High Altitude Wind Energy” (Aug 2011); available at: http://www.gl-garradhassan.com/en/highaltitudewind.php/

ergy systems, and has received comments from interested industries. In Near Zero's discussion, some experts expressed concern that the FAA rules would be a barrier for rapid testing of prototypes and also for implementation of large-scale systems. Another concern of some experts is the uncertainty about future regulations for large-scale systems.

Most of the remaining barriers in Near Zero's survey were technological. Control systems are crucial for reliability of airborne wind energy aircraft. They would need to stay aloft for long periods of time despite shifts in wind direction and adverse weather (including lightning storms and hail), and be able to control themselves so that most of the time they remain in a position to produce significant electricity.

Mechanical engineer Saul Griffith, co-founder of Makani Power, said that control systems are "extremely important" since "the fundamental problem of airborne wind energy is really a problem of autonomous control for very long periods of time." As an analogy, he said, "think of it as substituting controls for concrete" in the bases of traditional wind turbines. Control systems and other components of airborne wind systems could be taken "off the shelf" from the aerospace industry, argued Eric Blumer of Honeywell Aerospace, cutting down the time required for development.

Other aspects—tethers, operating costs, land use, air to ground transmission, scalability—were ranked as middle barriers. There was also general agreement that two areas were not major barriers: grid integration and electric generators.

Overcoming Barriers

When asked to allocate a hypothetical fund for research and development into several categories, the experts opted to spread the money across a variety of technologies and types of work that would be needed to test various approaches, and to help bring them toward commercialization (see **Fig. 4**).

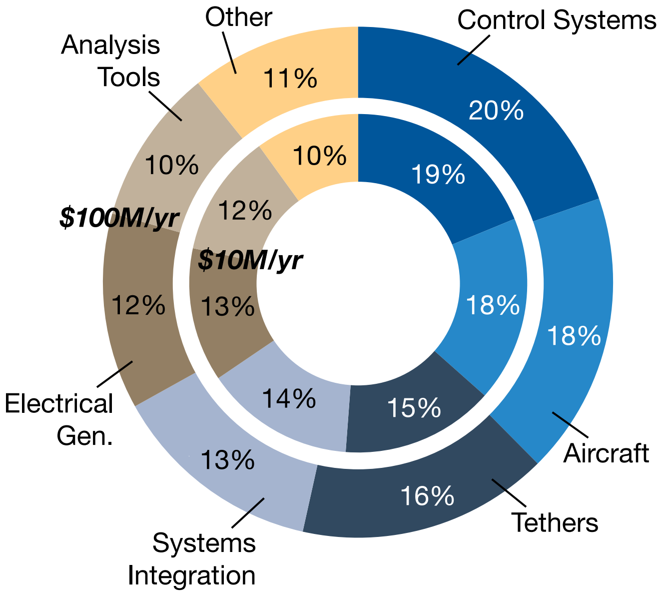

Figure 4 | Research and Development Priorities. On average, the top priority for R&D funding was aircraft, followed by control systems. The priorities were approximately the same regardless of funding level.

Aircraft and control systems were the top priorities. This reflected the ranking of barriers, and the fact that rigid wing systems would likely need more sophisticated control systems than would other types of systems. The experts' ranking of other R&D areas generally followed their rankings of barriers the industry faces.

If the government were to spend $10 million to bolster airborne wind energy, most experts thought the vast majority of the money should go to R&D. Only a few argued that the bulk of the money should go to market incentives. With $100 million on the table, the views changed somewhat. Although most still thought the bulk of the money should go to R&D, about a third thought that half or more the money should go to market incentives (see **Fig. 5**).

Many experts argued that airborne wind energy is in too early of a stage to benefit from market incentives. For example, Martin Hoffert commented: “This technology is nowhere near ready for commercialization. What we need now are demonstration projects of competitive ideas.”

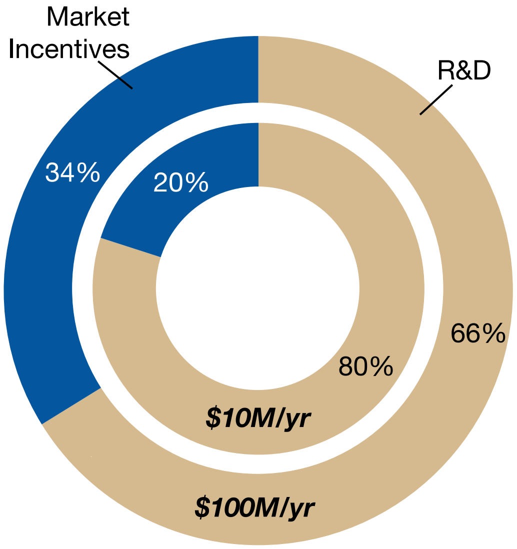

Figure 5 | Research and Development vs. Market Incentives. Most of the experts thought that the vast majority of the funding at this time should go toward R&D, with only a small amount for market incentives.

In the discussion, there was disagreement about whether the money would be better directed toward universities and government labs, or whether it should go to companies. In Near Zero’s discussion, Damon Vander Lind of Makani Power said, “For now, the most judicious use of funds may be to give promising companies not having fully functional prototypes enough money to complete and test fully functional prototypes, and to give those having fully functional prototypes budget to pursue utility scale prototypes. This would probably require a budget in the tens of millions rather than billions.”

But others directly involved in the burgeoning airborne wind industry did not necessarily favor funding going to companies. For example, Luciano Fagiano of Italy-based KITEnrg argued “R&D in universities and research centres is probably the most effective way to tackle the uncertain aspects of the different technologies.” One route for funding university research would be through a program known as NASA Research Announcements, said NASA researcher Mark Moore. “It would be great to achieve significant university involvement” in airborne wind energy, Moore said, adding that “supporting a broad spectrum of universities would ensure significant publications in open literature”—to the benefit of all players in industry and research.

Reaching Scale

To gauge how long it may take for airborne wind energy to reach commercial scale, Near Zero asked experts how long it might take to build and install enough systems to produce 1 gigawatt (1 billion watts) of electricity. (For comparison, starting from applications in satellites, the solar industry took about 40 years to reach cumulative commercial production of 1 gigawatt of solar panels.)

Near Zero asked how long it would take to reach 1 gigawatt in each of three cases: no support, $10 million per year, and $100 million per year (see **Fig. 6**). The experts’ answers diverged widely, with some saying airborne wind energy could reach 1 gigawatt within a few years, while others said it would take many decades—perhaps 50 years or more. But all agreed that with no government support, it would take far longer for airborne wind energy to scale up.

To reach 1 gigawatt, on average the experts said:

- with no support, it would take 20 years
- with annual funding of $10 million it would take 15 years
- with annual funding of $100 million it would take 9 years.

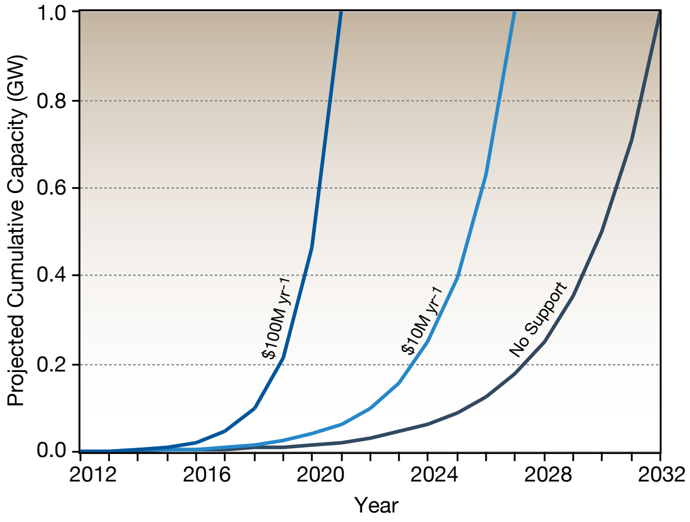

Figure 6 | Growth. Government spending on airborne wind would help airborne wind energy scale up, the experts agreed—and more money would help the approach reach scale quicker.

Conclusions

While there were divergent opinions on many aspects of airborne wind energy, there were many areas of agreement that emerged from the survey and discussion. The experts in the Near Zero survey thought that the most promising type of aircraft, where the bulk of research funds should go, is rigid-wing aircraft. Likewise, research funding should concentrate on aircraft and control systems for these aircraft. Significant funding for research could jumpstart the industry, allowing many companies to cross the “valley of death” from prototype stage to commercial viability, and helping the industry roll out significant amounts of airborne wind energy systems in the coming decade.

APPENDIX 1 - Expert Participants

Table A1 | List of Participants. Asterisks indicate participation in the formal survey.

*Ian Alers	Parsec Aero
Douglas Amick	Amick Global
*Cristina Archer	University of Delaware
Matt Bennett	WindLift
Eric Blumer	Honeywell Aerospace
JoeBen Bevirt	Joby Energy
*Alexander Bormann	EnerKite
*Stephan Brabeck	SkySails
Ken Caldeira	Carnegie Institution for Science
*Grant Calverley	Skymill Energy
*Dimitri Chernyshov	Highest Wind
*Rob Creighton	WindLIft
*Moritz Diehl	Catholic University Leuven
Gabriel Hugh Elkaim	University of California, Santa Cruz
*Lorenzo Fagiano	Kitenrg and Politecnico di Torino
Allister Furey	University of Sussex
*Kurt Geebelen	KU Leuven, OPTEC
Ben Glass	Altaeros Energies
*Saul Griffith	Otherlab and Makani Power
*Sébastien Gros	Catholic University Leuven
*Corwin Hardham	Makani Power
*Martin Hoffert	New York University
*Corey Houle	SwissKitePower
Peter Lissaman	Da Vinci Ventures
*Guido Luetsch	NTS Energy & Transports
*Robert Lumley	KiteFarms
*Pete Lynn	Peter Lynn Kites
Mario Milanese	Kitenergy srl
Pedram Mokrian	Mayfield Fund
*Mark Moore	NASA Langley Research Center
*Carlo Perassi	Wind Operations Worldwide SpA
*Chris Purvis	Edison International
*Adam Rein	Altaeros Energies
*Andreas Reuter	Leibniz University of Hannover
*P.J. Shepard	Sky WindPower
*Sara Smoot	Stanford University
*Michael Strobel	Fraunhofer Institute for Wind Energy Systems (TWES)
*Damon Vander Lind	Makani Power
*Becker van Niekerk	Parsec Aero
*Bruce Weddendorf	Sky WIndPower
*Robert Wilson	Oregon State University
*Udo Zillmann	Daidalos Capital

APPENDIX 2 - Survey Questions and Responses

Preferences for types of aircraft

Questions asked: If the government were to allocate $10 million per year to R&D support over the next 5 years, what fraction would you allocate toward the research and development of different types of aircraft? (Choices were: Balloon, Soft Wing, Rigid Wing, Other) We'd like to better understand the marginal returns on higher levels of R&D funding. How would your allocation change if the government were to allocate $100 million per year over the next 5 years? (Same choices as in previous question.)

The results show that rigid-wing aircraft were favored by most experts, but there were still some who thought that substantial amounts of funding should go to other types of aircraft, primarily soft-wing aircraft. Balloons were consistently the least favored type of aircraft. The results were similar regardless of the amount of money in the hypothetical fund.

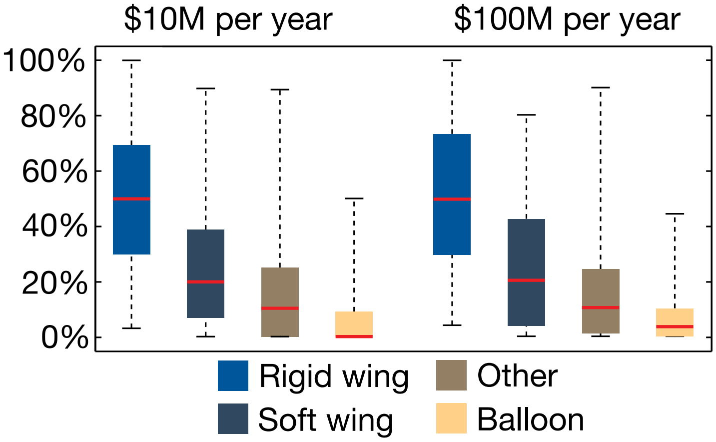

Figure A1 | Preferred types of aircraft. Each box-and-whiskers plot shows the statistical distribution of expert responses, with the red line indicating the median, the colored box bounding the 25th to 75th percentiles and the dashed whiskers spanning the full range of answers.

Favored types of technology for generating electricity

Questions asked: If the government were to allocate $10 million per year over the next 5 years, what fraction would you allocate to Flying Power Generation vs Ground-Based Power Generation? (Choice of the fraction that would go to flying generation, with the remainder going to ground generation.) What if the government were to allocate $100 million per year over the next 5 years? (Same choices as in previous question.)

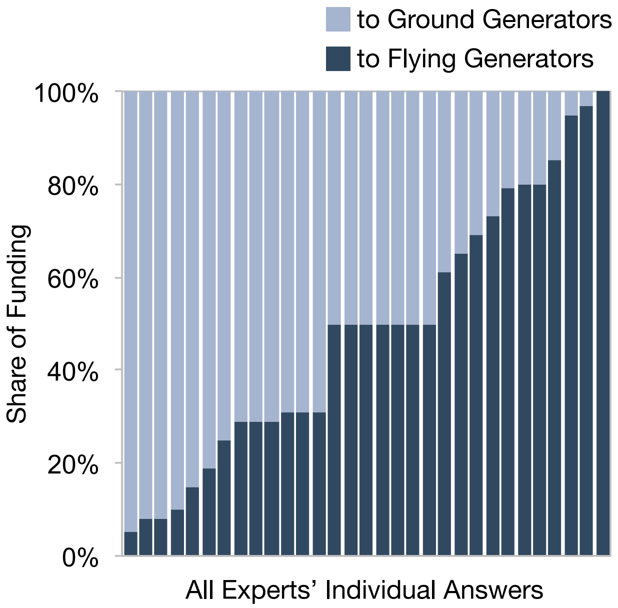

Figure A2 | Favored types of electric generator at $100M per year funding.

The results show that the experts' answers were equally spread across the options, from devoting all the funding to ground-based generators to putting all the funding toward flying generators. The results were similar regardless of the size of the fund being considered. The lack of agreement over which approach to use suggests that, for now, both approaches should receive substantial funding.

Large-scale vs. small-scale system

Questions asked: If the government were to allocate $10 million per year over the next 5 years, what fraction would you allocate to Small-Scale, Distributed Systems versus Utility-Scale power systems (Choice of the fraction that would go to Distributed Systems, with the remainder going to Utility-Scale Systems.) What if the government were to allocate $100 million per year over the next 5 years? (Same choices as in previous question.)

In the case of a smaller fund of $10 million per year, the experts split fairly evenly, with roughly equal numbers choosing to give less than a third, a third to two-thirds, or more than two-thirds of the money to small-scale, distributed systems. However, when the fund considered was $100 million per year, then a clear preference emerged for spending the bulk of the money on large-scale systems.

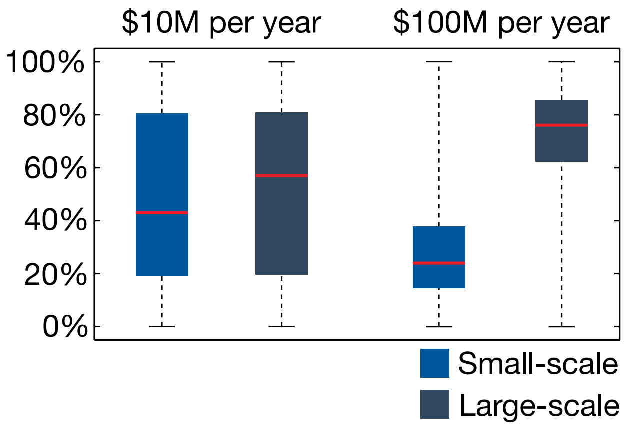

Figure A3 | Favored scale of airborne wind energy systems. Each box-and-whiskers plot shows the statistical distribution of expert responses, with the red line indicating the median, the colored box bounding the 25th to 75th percentiles and the dashed whiskers spanning the full range of answers.

Ranking barriers to development of airborne wind energy

Question asked: Please rank the following barriers to demonstrating a commercially viable AWE [airborne wind energy] system. Note that in several cases the barriers may be either technological or the cost of overcoming the technological barrier. (Options were: Grid integration, Government regulation, Tethers, Reliability, Land Use, Control systems, Electrical generators, Air-to-ground energy transmission, Scalability, Operating costs, Largest Barrier, Smallest Barrier)

Experts were asked to rank the barriers to the development of airborne wind, from the highest barrier to the lowest barrier.

The barriers on the left of Figure 3 in the main body of the report are listed in order from the highest-ranked barrier (reliability) to the lowest ranked (electric generators), based on aggreate scores from all the experts' responses. The number of votes for each ranking is listed in the grid. (For example, reliability received 12 votes as the highest barrier, and 6 votes as the second-highest barrier. Likewise, electric generators received 5 votes as the lowest barrier.)

Priorities for R&D spending

Questions asked: If the government were to allocate $10 million per year to R&D support over the next 5 years, what fraction would you allocate to research and development of: Aircraft, Electrical Generation, Systems, Tethers, Control Systems, Systems Integration, Analysis Tools, Other? Again, because we'd like to better understand the marginal returns on higher levels of R&D funding. How would your allocation change if the government were to allocate $100 million per year over the next 5 years? (Same options as in previous question.)

On average, the top priority for R&D funding was aircraft, followed by control systems. But there were a wide variety of answers from individual experts, with no obvious correlation between their funding allocations between different categories of spending. Shown above are the results for the hypothetical $100 million per year fund; results are similar for a $10 million per year fund.

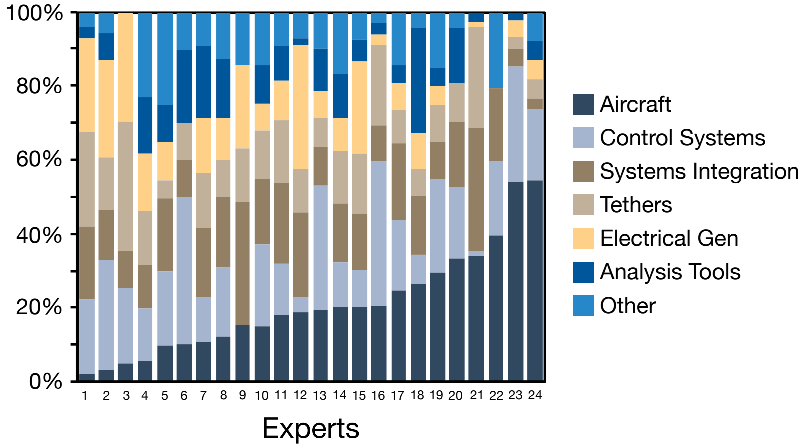

Figure A4 | Research and priorities of surveyed experts assuming $100M per year funding.

Government spending: R&D vs. market incentives

Questions asked: If the government were to allocate $10 million per year over the next 5 years, what fraction would you allocate to market incentives (e.g., subsidies, guaranteed markets, etc) versus direct government R&D support (to industry / academia)?

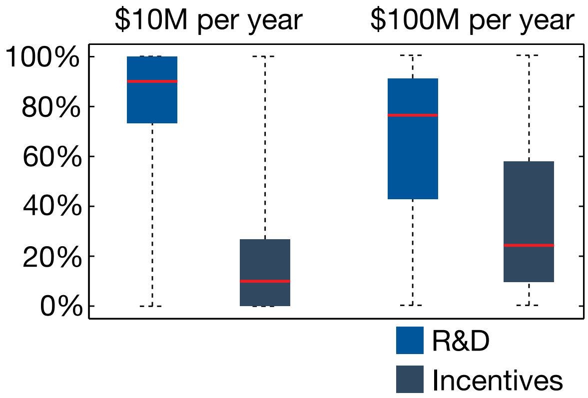

Figure A5 | Expert preference for funding R&D vs. market incentives. Each box-and-whiskers plot shows the statistical distribution of expert responses, with the red line indicating the median, the colored box bounding the 25th to 75th percentiles and the dashed whiskers spanning the full range of answers.

(Choice was the fraction that went to "market incentives," with the remainder going to "R&D support." Then the same question was asked for a fund of $100 million per year.)

The results showed that the vast majority of experts thought that the bulk of the money (more than two-thirds) should go toward government-directed R&D. For the larger of the two funds, more experts tended to allocate a sizeable portion of the money to market incentives, but most still put the bulk toward R&D.

Time required to scale up to 1 GW

Questions asked: How many years do you estimate it would take to reach 1 GW of cumulative deployment with no government R&D support? What about with $10 million/year of government R&D support? What about with $100 million/year of government R&D support?

The results show that with more government spending on airborne wind, the experts expect that it will take less time to scale up to a total of 1 gigawatt (1 GW, or 1 billion watts) of airborne wind energy capacity. There were some experts who thought that this scaling up would take 40 years or more with no government support (see blue line), but with increasing amounts of support, the number of experts who thought it would take a very long time dropped off (green and yellow lines).

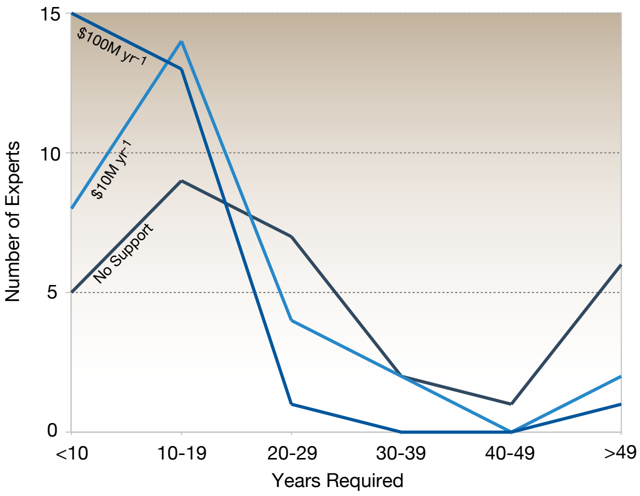

Figure A6 | Years required to scale up airborne wind energy to 1 GW in three funding scenarios.