ROUGH SEAS FOR THE SUPERCONDUCTING WIND TURBINE

TO KEEP OFFSHORE TURBINES LIGHT, ENGINEERS LOOK BEYOND SUPERCONDUCTORS TO A NEW PERMANENT-MAGNET TECH

By SAMUEL K. MOORE

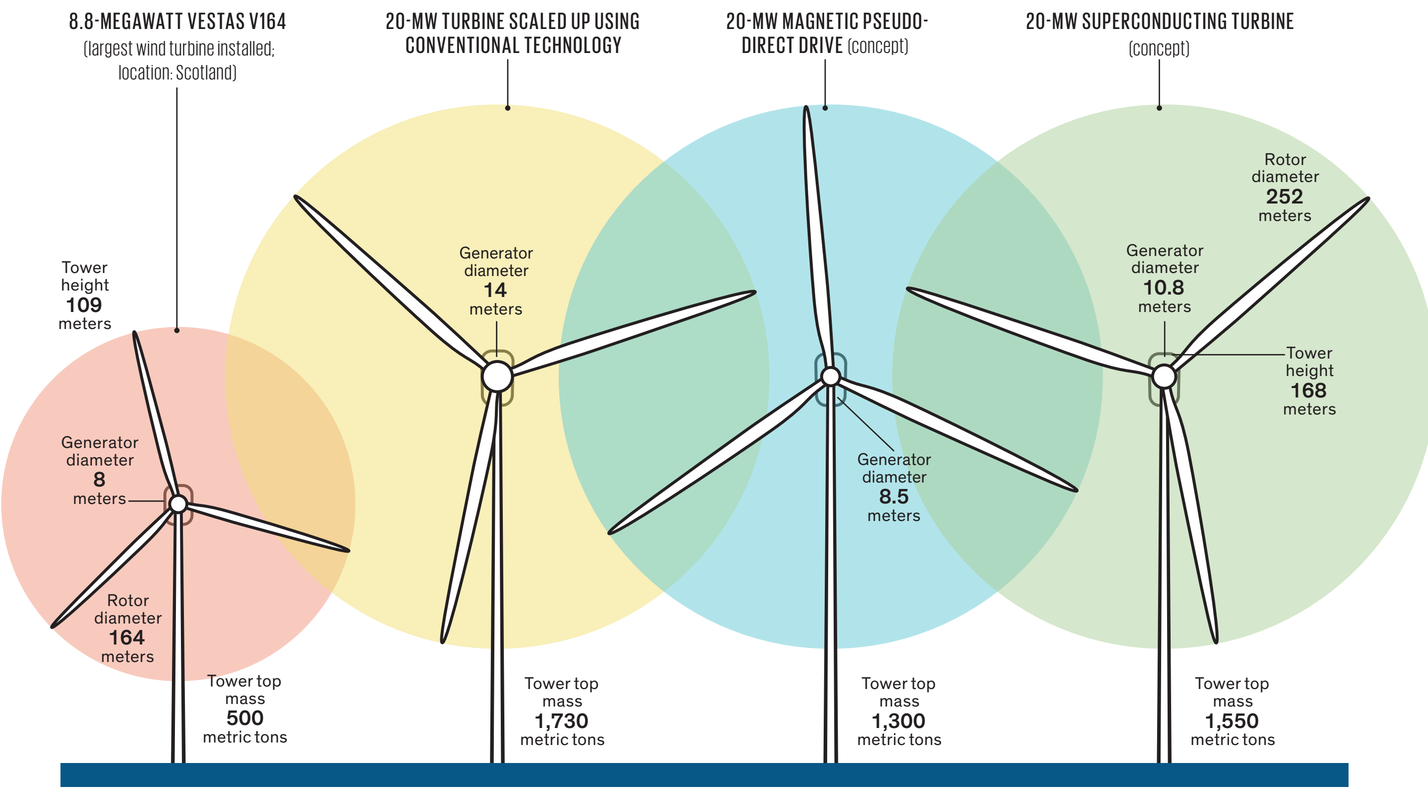
TRY TO WRAP YOUR HEAD AROUND THIS: A slender tower stretches 100 meters above the waves. Blades, each one of them nearly 60 meters long, face down the briny spray as they turn about a 250-metric-ton nacelle at the top of the tower, which houses the turbine generator and everything else needed to produce electricity.

Now double the size of everything, and make it five times as heavy.

That's the problem that will eventually face builders of offshore wind farms. In general, bigger—more megawatts per turbine—is better. So wind farm operators have been demanding higher-power offshore turbines, and manufacturers have been delivering. The most powerful turbine yet installed, an 8.8-megawatt machine from Vestas Wind Systems, went up off the coast of Scotland in April, and bids for some upcoming North Sea wind farms were made with the expectation that 13- to 15-MW turbines would be available by the middle of the next decade. Such turbines could power about 9,000 homes while the wind is blowing. But though bigger might be better, without some equally big changes in the wind turbine's core technologies, bigger quickly becomes ludicrous.

Massive Machines

Today's biggest offshore turbine is dwarfed by proposed 20-megawatt turbines. Low-cost systems designed by the InnWind consortium show superconductors [far right] making for a less-massive system. But an upstart permanent-magnet technology [second from right] is lightest.



A European Union project called InnWind calculated that if a 20-MW wind turbine were to be built with today's technology, its nacelle alone would weigh nearly 1,100 metric tons (the mass of 11 blue whales). The turbine's three blades themselves would weigh nearly 40 metric tons each and span a diameter of more than 250 meters (8 blue whales in length). The tower beneath this monster of megawatts would need to weigh nearly 1,800 metric tons to hold up all of these structures some 170 meters above the waves. To complete the picture: That's 18 blue whales holding up 11 others with 8 more spinning like a cetacean pinwheel. (You're welcome.)

"The problem is that there is a limit for constructing with current technology," says Iker Marino, an electrical engineer in the renewable energy and storage systems group at the Spanish applied-research organization Tecnalia Corporación Tecnológica and coordinator of an EU superconducting turbine project called Suprapower. "The weight of the top of the machine is too huge."

So how do you remove hundreds of tons from the mass of a machine made of magnets, gears, iron cores, and kilometers of copper winding? Exchange the magnets and maybe even the copper winding for coils of superconductors.

Simple, right? Actually, no. Years-long multinational research efforts have recently concluded that, while feasible, building such a turbine would be a monumental tech challenge. And the case for doing so is weakening as permanent magnets get better and cheaper. In fact, a dark-horse competitor whose technology is based on permanent magnets is on track to nudge superconductors aside in the 10-MW realm. And unless either the economics or the attributes of superconductors greatly improve—and, actually, both things are indeed possible—even future 20-MW titans of the sea might be superconductor-free.

WIND TURBINES ARE COMPLICATED. They operate as a result of an interplay of mechanical, magnetic, and electrical processes that change in complex ways with every tweak of a parameter. Nevertheless, they all have essentially the same set of basic conditions and components. The blades turn at a pretty stately pace, though with a great deal of torque. That slow speed is far from ideal for generating electricity, so in geared turbines—the majority, particularly onshore—a gearbox steps up the speed hundreds of times, devoting that rapid rotation to the spinning of the generator.

PREVIOUS PAGES: HOWARD LITHERLAND/ALAMY

ILLUSTRATION BY James Provost

But in an effort to reduce maintenance costs, some manufacturers are turning to an alternative offshore turbine technology called direct drive, which requires no gearbox. Here, the rotor is a gigantic ring holding many permanent magnets with alternating polarity. The generator's other key component—the stator—surrounds the rotor. It contains coils of copper wire where voltage is induced by the rotor's magnetic field.

Basically, superconductors can reduce the weight of a generator because they can replace the direct drive's permanent magnets with lighter electromagnets made from coils of superconducting wire. These electromagnets are comparatively light because superconductors can carry an enormous amount of current—that is, they have a high current density. Copper conductors in such machines top out in the single digits of amperes per square millimeter cross section. In the experimental superconducting turbine winding built for the Suprapower 10-MW turbine project, current density leaps to an astounding 58 A/mm^2.

Much has been made of the potential of high-temperature superconductors, such as yttrium barium copper oxide (YBCO), because they become superconductive at temperatures below 90 kelvins—warm enough for cooling with cheap liquid nitrogen instead of very costly liquid helium. And a leading YBCO maker, AMSC, produced a rough turbine design several years ago. (The company did not respond to requests for comment on this article.) But most of the recent European superconducting wind turbine projects have independently settled on a different superconductor: magnesium diboride.

Magnesium diboride's superconductivity was discovered only in 2001, and although it doesn't lose its resistance until it dips below 40 K, it's so much less expensive that it beat YBCO in every cost analysis. At about €4 (US $4.63) per meter of tape, MgB_2 is "maybe not the material that gives the best performance, but it gives the best cost performance," says Marino.

Columbus Superconductors, based in Genoa, Italy, is a leading MgB_2 wire supplier and was a partner in Suprapower and in an earlier U.S. Department of Energy project. The company has also contributed to InnWind and a recent French project called EolSupra20.

Of these, Suprapower most recently produced something tangible. The project, which ended in May 2017, was a €5.4 million ($6.25 million), five-year affair intended not only to design a 10-MW direct-drive superconducting turbine generator but also to build a critical part of the design—two of the 48 superconducting electromagnet coils that would make up a full rotor. The design calls for a 163-metric-ton generator, a mass reduction of 26 percent over what the thing would weigh if constructed with today's permanent-magnet technology.

The rotor coils are made from a flattened copper wire in which an MgB_2 wire has been embedded. The copper reinforces the comparatively brittle MgB_2 and conducts heat away from it. For Columbus, the geometry of the coils was the difficult part, says Gianni Grasso, the company's managing director during the project. These "racetrack" coils are roughly rectangular in shape, and the sharp corners produce stress on the wires that could crack the superconductor. "We had to develop a specific tool to do the winding," he says.

Finding a way to keep the windings at 20 K—and do that out at sea—was an even greater challenge. "All the engineering around heat extraction is feasible but complex," says Marino. "Offshore conditions are a problem for complexity."

Usually superconductors, such as those in MRI machines, are cooled by bathing them in a cryogenic fluid like liquid helium. But Suprapower ruled that option out. During any kind of maintenance at sea, that fluid would have to be removed to warm up the generator's innards and then replaced. Handling such a fluid at the top of a wind-buffeted tower and hauling around the equipment needed to reliquefy the gas just didn't seem practical.

Instead, Suprapower's engineers chose to cool the coils by conduction. Gifford-McMahon cryocoolers would provide the cooling power to a distributed set of modular cryostats—enclosures that maintain the temperature of what's inside them. Each superconducting coil in this modular system has its own cryostat, which was designed to keep the coil in a vacuum.

The hope, Marino says, is that the modular nature of these cryostats will make maintenance easier. In the event that it or the coil it encloses needs replacing, a technician would have to bring only that particular segment up to room temperature and then cool its replacement back down. That convenience could speed repairs, though Marino expects that maintenance would still take longer than on a conventional machine.

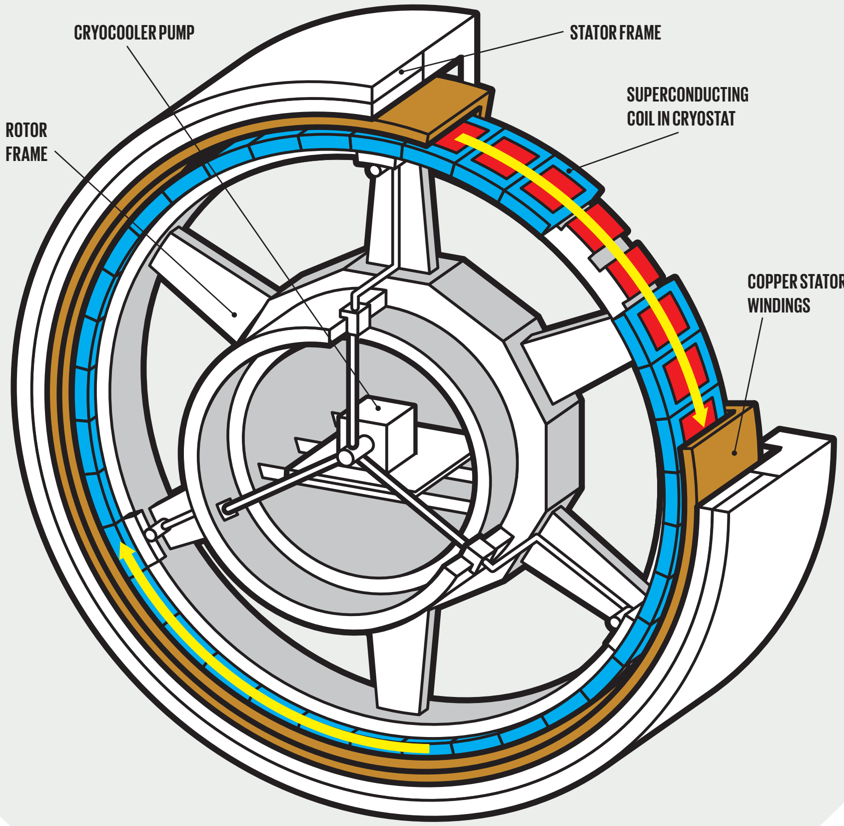
THOUGH SUPRAPOWER was able to build a critical piece of a superconducting wind turbine, it didn't answer the question of whether it, or even bigger superconducting turbines, should be built at all. That was the goal of InnWind. The €20 million ($23.2 million) project, begun in 2012, developed several designs based on a variety of new technologies, including MgB_2 superconductors. It aimed to design complete 10- and 20-MW wind turbines for use in 50 meters of water at the lowest cost possible, thereby pointing the way toward the future. A funny thing happened on the way to the future, however: It got more complicated.

In the last five years, the price of the kinds of permanent magnets needed for advanced turbines has fallen by more than a factor of four, to about €25 ($29) per kilogram. Asger Bech Abrahamsen, the senior researcher at Technical University of Denmark's wind energy department who led the drivetrain design efforts for InnWind, says, "With that kind of input price level, superconducting machines can't compete."

InnWind researchers sought systems that resulted in the lowest levelized cost

Superconducting Wind Turbine

A 10-megawatt turbine generator designed as part of the Suprapower project uses magnesium diboride superconductors as the rotor's electromagnets. Each of the 48 magnets is cooled to below 40 kelvins and sits in its own cryostat.



of electricity (LCOE) for the whole turbine, including the foundation, tower, and blades. LCOE is basically the price a turbine needs to get for its electricity, over its lifetime, to break even. That figure takes into account manufacture, construction, maintenance, efficiency, decommissioning, and other factors and is among the key metrics that wind farm investors use to decide what to build—and where.

In InnWind's quest for the lowest LCOE, the fall of permanent-magnet prices forced it to reduce the amount of superconductor in its 10-MW superconducting turbine designs and to add magnetic steel to help concentrate the remaining superconductor's magnetic field. InnWind then had to add even more steel because of an unexpected resonance in the structure. This problem resulted from the mass at the top of the tower being so light that when the 41.7-metric-ton blades swung past the tower, they strained the structure at a frequency that was too close to its natural frequency. Eventually, that strain would have shortened the substructure's required 25-year lifetime. Also—and most unfortunately—simulations showed that the resonance was stronger the *lighter* the turbine generator became, explains Abrahamsen. Faced with a situation in which making the generator lighter would lead to a more costly substructure, the InnWind designers allowed the mass of the 10-MW superconducting drivetrain to balloon to 286 metric tons, compared with the 215 to 237 metric tons for scaled-up versions of permanent-magnet-based direct-drive tech.

Though InnWind's 20-MW MgB_2 design didn't have the resonance problem, it still needed a lot of steel to make up for the design's reduced amount of superconductor. With superconductors, the instinct is to make the lightest, smallest turbine generator possible, says Abrahamsen, but from the perspective of low LCOE, "we had to conclude that a lightweight generator as always beneficial is not quite always true."

THE PRICE COLLAPSE OF PERMANENT MAGNETS also opened an opportunity for a dark-horse competitor to superconductors. Called the magnetic pseudodirect drive (PDD), it's a kind of magnetic gearing system in development at Magnomatics, based in Sheffield, England.

The system is hard to fully grasp unless you see it in motion, but here goes: A PDD is a set of three concentric cylinders. The inner and outer rings are each made up of stripes of permanent magnet with alternating polarities. The outer cylinder has many stripes, the inner just a few. The central cylinder consists of alternating stripes of steel and nonmagnetic support material. In operation, the outer ring is held stationary, while the turbine's low-speed input from the blades spins the central steel cylinder. That cylinder manipulates the magnetic lines of force of the outer cylinder's permanent magnets so that they form a magnetic field that rotates quickly and in the opposite direction of the steel cylinder. This field couples with the permanent magnets of the inner cylinder to produce high-speed rotation. To turn this gear into a generator, coils of copper wire are set around the outer ring, where they experience the same fast-moving magnetic field that the inner ring does. That fast-moving field induces a voltage in the coils of copper wire.

In InnWind's analysis, this setup beat the superconducting design on efficiency. PDD "gained most by having high efficiency even at low wind speeds," says Abrahamsen. "A superconducting machine can also reach a pretty high efficiency, but it needs a cooling system," which is a constant drain on energy even when the wind is barely blowing, he notes. While other factors, such as construction cost, are spread over the turbine's 25-year life, efficiency has a much more direct effect on cost.

"It doesn't sound like much, but 2 percent more efficiency means 2 percent on LCOE," says David Powell, principal engineer for drive technology at Magnomatics. And in the wind industry, he adds, "2 percent is a big deal."

The PDD gets that relatively high efficiency by adopting the smaller size of geared turbines without suffering from energy losses in mechanical gears. These losses can be 1 to 2 percent per stage, and many turbines have three gear stages, explains Powell. In the PDD, however, there are no mechanical connections; the cylinders float within each other separated by an air gap, so the system doesn't even need lubricant.

Though the main selling point in the wind industry is the PDD system's efficiency, it is also considerably smaller and requires much less copper winding than existing technology. The 10-MW PDD design's drivetrain mass was more than 100 metric tons lighter than the superconducting MgB_2 design. And the turbine was only 6 meters in diameter versus the reference design's 10 meters. That size difference may offer an advantage in manufacturing, Powell says, because it would give turbine makers the option of building new high-megawatt turbines in older, smaller factories.

Magnomatics plans to capitalize on this victory. But it has a lot to do to scale up to 10 MW or beyond. With conventional technology already in the water, little more than 1 MW away from that mark, "we need to get there very soon," Powell notes. "It's all happening for us now. We just have to catch the right people."

RAPHAËL PASQUET/CEA SACLAY/IEEE

MAGNESIUM DIBORIDE MASH: Filaments of the superconductor magnesium diboride are encased in ribbonlike support structures of copper and other elements. The ribbons are then carefully wound into a "racetrack" shape to form the turbine's high-power electromagnets.

THOUGH a nonsuperconductor technology won InnWind on cost, that consortium's analysis isn't the only one around. The smaller, French project called EolSupra20 aimed straight for the 20-MW mark with its LCOE exploration and came up with very different results.

Unlike those of others, EolSupra20's design includes MgB_2 superconductors in both the rotor and the stator. "What you want for the rotor is to create a really large magnetic field," says Loïc Quéval, assistant professor at the University of Paris-Saclay. So all you need is DC current, which in a superconductor flows without loss and generates no heat.

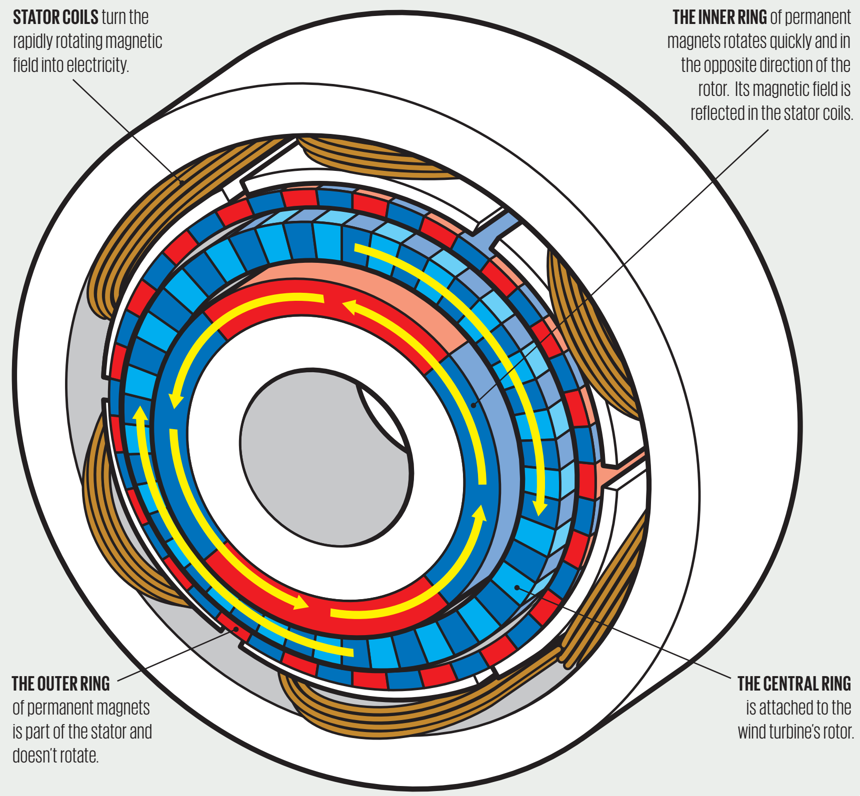
"The stator is something different," he says. As the rotor's magnetic field cuts through it, the current in the stator's windings changes directions. Amazing as they are, superconductors do experience some loss when carrying AC current. This had two effects on the design. First, it required a different form of superconducting wire to do the job. An alternating magnetic field causes loss-inducing loops of current in the surface of a superconductor. Unfortunately, superconductors—especially the high-temperature variety—are usually produced as tapes rather than wire, so they have lots of surface area on which these loops can form. "It's almost impossible to produce a low-AC-loss, high-temperature superconductor," says Columbus Superconductor's Grasso, whose company also produces such materials. "But it's possible with MgB_2."

Instead of the tape, Columbus has been working on an MgB_2 format with a smaller surface area. It's producing wires in which many round filaments of MgB_2 with diameters of 10 micrometers are embedded. These filaments have too small a surface area for many current loops to form, explains Grasso. In one format, 91 such filaments are embedded in a copper-and-nickel hexagonal wire. These wires would then be packed into a flat format called a Rutherford cable, although this has yet to be achieved at useful lengths.

ILLUSTRATION BY James Provost

Magnetic Pseudodirect Drive

A peculiar arrangement of permanent magnets turns a wind turbine's high torque into the quickly rotating magnetic field needed for a generator.



The second consequence of having a superconducting stator is that it must be cooled, and those cooling demands will be steeper than what the rotor needs. The EolSupra20 design uses a set of cryocoolers to keep the rotor at 10 K, a temperature that maximizes the superconductor's current-carrying ability. The stator is on a separate group of cryocoolers set to keep it at 20 K, because it would take too much power to maintain a lower temperature than that.

To meet these needs, the design calls for no less than 85 cryocoolers in total. "We put cryocoolers everywhere," says Quéval. Sourcing powerful cryocoolers was a problem, so EolSupra20 used multiple smaller ones. The Sumitomo Heavy Industries RDK-0408S2 two-stage cryocoolers that EolSupra20 used in its design weigh just 18 kilograms and can pull mere watts to tens of watts of heat from the coils—but at the expense of about 100 times that amount of energy. "Right now, efficiency is really low," Quéval says.

EolSupra20's superconducting design did manage to beat its version of a turbine built using conventional technology with respect to LCOE. It chimed in at €119 per megawatt-hour ($140/MWh) compared with €129/MWh ($152/MWh) for the conventional turbine. The difference, according to Quéval and the EolSupra20 team, was the substantially lower generator mass enabled by the superconductors. At 178 metric tons, the fully superconducting generator was barely more than one-third of the conventional generator's bulk.

EolSupra20's LCOE is quite noticeably higher than that of InnWind's reference 20-MW turbine, which is €93 ($108)/MWh. Quéval points out that LCOE is, to some extent, a local affair. InnWind's aim was the deeper waters of the North Sea, where competition is fierce and grid connections are planned, if not yet plentiful. Future wind farms have already been promised there at less than €100 ($116)/MWh. The Atlantic coast of France is a different environment, both economically and geographically. France currently has no offshore wind farms, despite having a long, windy coast. But since 2012, the country has awarded tenders for 3,000 MW of offshore capacity, at the lofty price of about €200 ($232)/MWh. That number could change—and soon. Seeing the unexpectedly rapid fall in prices in the North Sea, the French government began signaling a desire to renegotiate in March.

SO, GIVEN THE MIXED SIGNALS, which technology will rule the sea in the future, superconductors or PDDs? InnWind's is surely a comprehensive study, with five years of work by some 27 industrial and research entities. That said, even its reports admit to a lot of uncertainty. And InnWind judges both drivetrain technologies at the same level of readiness: "Test in laboratory."

A better question, and one that InnWind tries to answer, might be: What would it take for superconductors to match the PDD drive? According to Abrahamsen and his InnWind colleagues, a price reduction in MgB_2 similar to what happened to permanent magnets would go a long way. If MgB_2 tape cost €1 ($1.16) per meter instead of €4 ($4.64), a 20-MW design could add much more of it, making stronger magnets that need less cumbersome amounts of magnetic steel. But such a design would also require a tenfold reduction in the estimated cost of cryostats and cooling equipment to make it competitive. It's an open question whether the commercialization of massive superconducting wind turbines would create enough demand to lead to prices that low in either technology.

But price isn't the only thing that could change. The critical temperature at which a superconductor starts superconducting is what most people focus on, but it's really a triumvirate of conditions that leads to superconductivity. There is a critical current density above which the phenomenon collapses, as well as a maximum magnetic field. A fourfold boost in the critical current value, say, would have a similar effect as a price reduction, because you could produce a stronger field with one-quarter the amount of superconductor. Even better, it would allow for different drivetrain designs. "The better the wire, the more simple the rest of the system is," sums up Suprapower's Marino.

It's also possible that these LCOE analyses for extremely massive turbines are all a bit premature. Another EU project called EcoSwing aims to prove that a superconducting generator can compete at more modest scales, and its engineers have nearly done it. By March 2019, the €14 million ($16.3 million) project plans to have installed such a superconducting generator inside a modified 3.6-MW turbine on land, where the installation and maintenance are easier.

Unlike the high-megawatt offshore projects, EcoSwing is aiming for the middle of today's onshore market. Superconductor technology has let the designers double the turbine's power density, allowing for a 40 percent smaller turbine generator and a 15 percent cost reduction over those of market leaders, says Jürgen Kellers, EcoSwing's director at ECO 5, an engineering company that's one of the nine contributors to the project.

Apart from its size, the EcoSwing generator differs from the InnWind and other offshore designs in that EcoSwing uses a single large cryostat instead of many modular ones. It also relies on a high-temperature superconductor—yttrium barium copper oxide—instead of MgB_2. The company chose the former despite the cost, because it's easier to cool YBCO. "You might say MgB_2 is already at a cost that YBCO wants to be in the future," says Kellers. "On the other hand, cryogenics is not as straightforward and rugged as with YBCO."

On 22 May, the consortium completed testing of its generator at the Fraunhofer Institute for Wind Energy Systems' DynaLab, a facility that can provide the torque and other conditions to test full-scale wind turbine generators. It's the first superconducting machine ever to undergo such tests.

From the DynaLab, the machine will stop at the University of Twente, in the Netherlands, for some final assembly and then move by ship to Denmark for installation in the turbine. "Then we have the lift and see how the EcoSwing generator performs in the harsh conditions of the North Sea coast," says Kellers.

Magnomatics isn't too far behind with its magnetic pseudodirect drive. Its next stage is a 500-kilowatt generator, which it will test on a dynamometer at the National Renewable Energy Centre, in Blyth, England. From there "we're going to try to put a 2- to 3-MW machine in a nacelle and get real data," says Magnomatics' Powell.

The battle for future designs may have gone to the PDD, but the fight to prove whether either technology really works is just beginning. ■

DOCKING MANEUVER: Workers prepare to link a 3.6-megawatt superconducting generator [blue] to a machine that simulates the torque and other aspects of a wind turbine [gray].

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