WIND SYSTEMS MAGAZINE
MAINTENANCE
MAY 2014

WIND SYSTEMS

GIVING WIND DIRECTION

Maintenance

White Structure Flaking
in Gearbox Rolling Bearings

Conversation
Pat Shannon / ITW WindGroup

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I convinced myself that it was the deal of the century. Everybody could use a second car for those unforseen circumstances, right?

It wasn't much to look at, but I was certain it would serve its purpose well.

Only 13 years-old? No problem. Just over 180,000 miles? Who cares? For only $1,500, I couldn't go wrong.

As it turned out, buying that little gem was the best impulse purchase I've ever made.

Several years passed, and after selling my economically and environmentally unfriendly 11-MPG truck, the "second" car became my primary mode of transportation.

Renowned for its build quality and longevity, the boxy Swedish sedan carried me much further than I had ever anticipated. I pushed it past one mileage milestone after another.

At 225,000 miles, the odometer stopped working; the car didn't. I kept rolling. By my estimate, the little "backup" jalopy eclipsed the quarter-million mile mark before finding its final resting place in a junkyard.

In the end, its list of ailments included a faulty anti-lock module, a gaping hole in its heater core, a recurring misfire, and only one functioning windshield wiper (thankfully, it was on the driver's side).

I don't remember thinking much about it at the time. After all, I had gotten my "money's worth" out of it. I'd even joke occasionally—while it was still running—that my car was paying me.

Looking back, however, I wonder how much longer "White Lightning" (yes, I did name it; and yes, it was out of pure irony) would've lasted if I had made any effort to take care of it. My maintenance schedule for the car was non-existent. The oil may have been changed once a year.

White Lightning's longevity was a testament to top-tier engineering and build quality; its demise was a testament to my apathy toward maintenance due to a minimal investment.

We don't have that luxury in the wind energy industry.

With millions of dollars on the line, we can't afford to "drive it 'til the wheels (or in this case, rotors) fall off."

This is certainly not earth-shattering news to the wind industry, but it doesn't hurt to hear it every now and again. With an increasing number of turbines coming out of warranty, the emphasis on maintenance will also increase. We need to make sure we're up for the task.

The main focus for our industry is sustainability. That means keeping wind assets running as long as possible—not just past the end-of-warranty period; not just to the expected equipment lifespan; not just to the end of a PPA.

Let's continue to look beyond the generally accepted turbine lifespan, and instead see just how many miles we can clock on the ol' odometer.

That's why we place so much emphasis on maintenance here at *Wind Systems*. It's a cornerstone of our magazine because it's a cornerstone of our industry.

After all, nobody really wants to see billions of dollars worth of investment end up in an eerie wind turbine bone yard, do they?

Thanks for reading,

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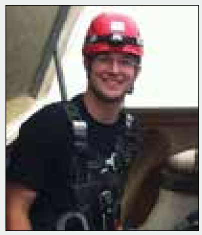
Contributors

Jack Wallace started in the wind industry as a wind turbine technician in 1985. Since then he has trained hundreds of technicians in electrical troubleshooting, mechanical systems, composites, and wind energy related safety. He has a deep understanding and experience of what it takes to run a wind farm and is always ready to help others in wind to successfully run their wind power plants.



Andrew Engle, E.I.T., is a graduate of Iowa State University with a Bachelors of Science in Mechanical Engineering. He works as a Mechanical Product Support Engineer for Availon Inc., an independent operations and maintenance service and parts provider for wind turbines in North America, based in Grimes, Iowa. His job involves supporting field personnel with troubleshooting of both mechanical and electrical systems and developing custom engineering and tooling solutions for wind turbine mechanical component problems. He is an ISO 18436-2 Level III vibration analysis certified and uses his background with machine design to evaluate failure modes of drive train components through vibration analysis and borescope inspections.

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DIRECTION

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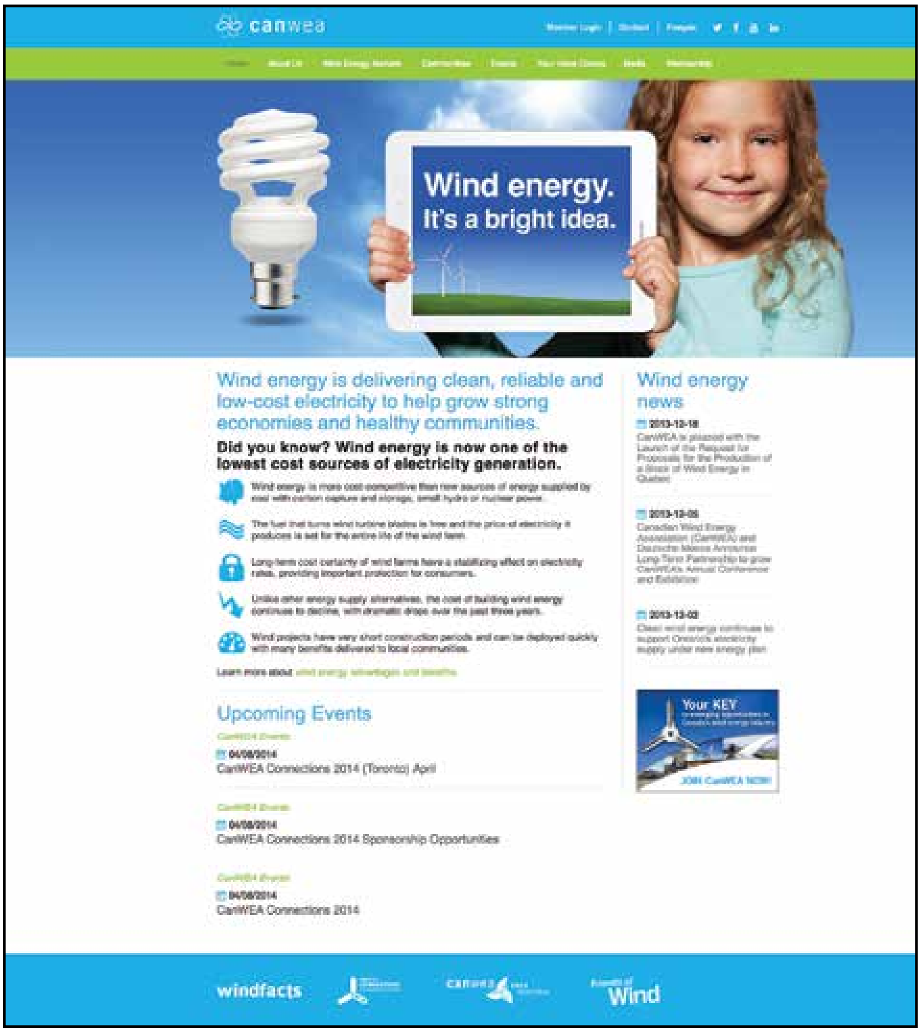
CanWEA revamps website for better user experience



The Canadian Wind Energy Association (CanWEA) is inviting visitors to explore its exciting new website. Re-designed to provide the ultimate user-friendly experience with improved navigation and functionality throughout, the site allows anyone with an interest in the wind energy sector in Canada to access detailed information and videos, and to share that information across all major social networking platforms.

"We are thrilled to announce the launch of our new website which includes extensive information for the general public, media and anyone interested in learning more about the wind energy industry in Canada," said Robert Hornung, CanWEA president. "Market information, videos and a photo gallery all work together to provide a detailed overview of Canada's wind energy sector," he added.

The new website, located at www.canwea.ca, provides visitors with general information about the association, career opportunities, an event schedule, and membership information. In addition, the association has provided valuable market information on the nation as a whole, as well as individual provinces. Users can also learn general wind facts, as well as information about small wind, case studies, wind farm planning, and stakeholder engagement.

The association also seeks to engage the public in championing wind energy through its online community section emphasizing advocacy for Canadian wind energy.

Media will find an interactive media room with up-to-the-minute news on Canada's wind energy industry, information on CanWEA spokespeople, videos, and more. CanWEA's 300+ members are Canada's wind energy leaders—owners, operators, manufacturers, project developers, consultants, service providers, and other organizations that support and participate in Canada's wind energy industry.

Visit the new website at www.canwea.ca.

Xcel Energy retains top spot among U.S. wind providers

For the tenth consecutive year, Xcel Energy has been named the country's top wind energy provider, according to the American Wind Energy Association's U.S. Wind Industry Annual Market Report, Year Ending 2013. For a decade, Xcel Energy has led the nation in providing wind energy to its customers.

"Xcel Energy is proud to be among the nation's leaders in delivering affordable, clean energy from renewable sources," said Ben Fowke, chairman, president, and CEO of Xcel Energy. "We embraced wind energy early because it's clean, cost-effective, and will protect our customers against rising fuel prices in the future."

As of 2013, Xcel Energy had 5,080 MW of wind energy on its systems, enough wind power to meet the energy needs of about 2.5 million homes. Wind also was about 15 percent of the company's energy supply, and by 2020 Xcel Energy projects it will be more than 20 percent.

Through state-of-the-art wind forecasting tools, Xcel Energy continues to save customers money and set national records for the amount of wind energy on its system. One early morning hour in May 2013, wind energy provided more than 60 percent of Xcel Energy's electricity supply on its Colorado system, which is a national record. The company also estimates it has saved $37.5 million in fuel costs since working to improve wind forecasting in 2009.

"We've been fortunate to operate in states with both excellent wind resources and policies that support the fair and cost-effective development of wind power," said Frank Prager, vice president for policy and strategy at Xcel Energy. "These things have enabled us to increase the use of renewable energy and to reduce emissions at a reasonable cost for customers."

Leading the nation in wind energy over the past decade also has played a key role in Xcel Energy's efforts to reduce carbon emissions. The company is well ahead of its goal of reducing carbon emissions 20 percent by 2020 compared to 2005 levels, and projects a 31 percent reduction by 2020.

Last year, Xcel Energy announced plans to expand its wind power use by another 40 percent over the next several years. The company is finalizing approvals and agreements to participate in nine new projects that will add a total of 1,900 megawatts throughout its service territory, enough to serve about 900,000 homes. The projects are being offered at prices competitive with new natural gas-fueled generation and are estimated to save customers more than $900 million over the length of the contracts.

Also in 2013, the American Wind Energy Association recognized Xcel Energy as the Utility of the Year for the second time in five years for the company's commitment to new wind energy acquisitions and progressive wind integration efforts.

Vestas, Mitsubishi finalize offshore joint venture

Final closing of the joint venture between Vestas and Mitsubishi Heavy Industries (MHI), dedicated to offshore wind power, has now taken place. The new company, MHI Vestas Offshore Wind, has 380 employees and is headquartered in Aarhus, Denmark.

Following the approval from all relevant authorities, MHI Vestas Offshore Wind has been formally established as of April 1. The joint venture is responsible for the design, further development, procurement, manufacturing, installation, commissioning and service related to the V164-8.0 MW turbine as well as all marketing, sales and after-sales service related to offshore wind. Vestas and MHI have transferred a total of 380 employees to the new entity, which is owned equally by the parent companies.

Anders Runevad, CEO of Vestas Wind Systems A/S and Vice Chairman of MHI Vestas Offshore Wind, is confident about the future of the new joint venture and said: "The Offshore wind power industry is very challenging and it takes just the right combination of reliable and proven technology, experience, knowledge and track record to succeed. I am confident that MHI Vestas Offshore Wind has exactly that right combination and I look forward to closely following the company towards becoming a global leader in offshore wind power."

"I am pleased to see MHI Vestas Offshore Wind now being operational. Vestas and Mitsubishi Heavy Industries each hold invaluable experience and knowledge which makes this joint venture an ideal opportunity and a technologically and financially robust platform to obtain a global leadership position within offshore wind," said MHI Vestas Offshore Wind board chairman Masafumi Wani.

HEADLINES

Nordex targets further growth and improvement in earnings in 2014

On the basis of its audited consolidated financial statements, Nordex confirms the preliminary figures for 2013 which it had reported in February. Thus, consolidated sales rose by around 33 percent to EUR 1,429.3 million (previous year: EUR 1,075.3 million), with return on sales widening to 3.1 percent. Consolidated profit after interest and taxes amounted to EUR 10.3 million, compared with a loss of EUR 94.4 million in the previous year, which arose mainly as a result of exceptional expenses in connection with the strategic realignment of the Group.

The gross margin expanded from 21.4 percent to the planned level of 22.6 percent in 2013.

This substantial improvement reflects operating measures such as cuts in the cost of materials of an average of around EUR 100,000 per turbine, more profitable contracts with new products and more professional execution of projects.

This development was particularly encouraging as Nordex's production and installation output simultaneously reached a new record. Thus, turbine assembly output rose by 48 percent to 1,342 MW, while installations of new wind turbines increased by 36 percent to 1,254 MW.

In this way, Nordex was able to outperform industry trends and double its market share to almost eleven percent in its core EMEA region. In addition, Nordex installed wind power systems in South Africa and Uruguay for the first time. Consequently, Nordex is once again amongst the world's ten largest producers of onshore wind turbines.

Energy Department to Issue $4 Billion in Loan Guarantees for Renewable Energy Technologies

The Department of Energy issued a draft loan guarantee solicitation today for innovative renewable energy and energy efficiency projects located in the U.S. that avoid, reduce, or sequester greenhouse gases. When finalized, the solicitation is expected to make as much as $4 billion in loan guarantees available to help commercialize technologies that may be unable to obtain full commercial financing. This draft solicitation represents another step in the Department's commitment to help overcome the financial barriers to the deployment of innovative, clean energy technologies.

"Through our existing renewable energy loan guarantees, the Department's Loan Programs Office helped launch the U.S. utility-scale solar industry and other clean energy technologies that are now contributing to our clean energy portfolio," said Secretary Ernest Moniz. "We want to replicate that success by focusing on technologies that are on the edge of commercial-scale deployment today."

The Renewable Energy and Efficient Energy Projects Loan Guarantee solicitation is intended to support technologies that are catalytic, replicable, and market ready. Within the draft solicitation, the Department has included a sample list illustrative of potential technologies for consideration. While any project that meets the eligibility requirements is eligible to apply, the Department has identified five key technology areas of interest: advanced grid integration and storage; drop-in biofuels; waste-to-energy; enhancement of existing facilities; and efficiency improvements.

The Department welcomes public comment on a range of issues and will consider public feedback in defining the scope of the final solicitation. In addition to initiating a 30-day public comment period, a schedule of public meetings will be posted on the Department's website. The draft solicitation can be found online at http://lpo.energy.gov.

Once the solicitation is finalized, the Department's Loan Programs Office (LPO) will be accepting applications in three areas, which also include the $8 billion Advanced Fossil Energy Projects Solicitation that was released in December 2013 and the $16 billion Advanced Technology Vehicle Manufacturing (ATVM) loan program. Currently, the LPO supports a diverse portfolio of more than $30 billion in loans, loan guarantees, and commitments, supporting more than 30 projects nationwide. The projects that LPO has supported include one of the world's largest wind farms; several of the world's largest solar generation and thermal energy storage systems; and more than a dozen new or retooled auto manufacturing plants across the country.

DNV GL ANNOUNCES WINNERS OF WIND ENERGY AWARD FOR YOUNG PROFESSIONALS

DNV GL recently announced the winners of its 3rd Annual Wind Energy Award at EWEA 2014 in Barcelona. Themed “Innovative ideas for wind energy,” DNV GL’s award recognizes and rewards young industry professionals’ forward-looking concepts and creative ideas for new technical approaches to research and development within the wind industry.

As the offshore wind industry continues to pick up pace, finding qualified experts with the required technical and practical knowledge is becoming increasingly challenging. Promoting young talent to pursue a career in the wind energy sector is crucial to ensuring future innovation and the sustained technical progress of the industry.

“Having reviewed the award entries this year I’m filled with confidence that the next generation of wind energy engineers will more than live up to that challenge,” says Andreas Schröter, executive vice president of Renewable Certification at DNV GL. “The number and quality of entries demonstrated an outstanding breadth of creativity, adding real value to concrete challenges the wind energy is facing.”

Schröter presented the €5000 (apprx. $6900) first place prize to Christian Hermann for his paper on ‘Analysis and modelling of maritime transport concepts for route and mission planning of operational and maintenance of offshore wind parks and its software technical implementation.’

Second place was awarded to Tom Probst’s for his paper on ‘Service life analysis of grouted connections for an offshore wind energy plant.’ Roderick den Ouden took third place for his work on ‘Conceptual and control design of a wind turbine blade installation tool.’

White Structure Flaking in Rolling Bearings for Wind Turbine Gearboxes

By Hideyuki Uyama and Hiroki Yamada, NSK Ltd.

An investigation into the failure modes yielding white structure flaking and axial cracking in wind turbine gearbox rolling bearings

Premature failures of rolling bearings occasionally occur in wind turbine gearboxes [1]. One of the main failure modes is flaking involving a microstructural change. This type of flaking is called white structure flaking (WSF) or white etching crack (WEC) because the area of the microstructural change observed in the flaking cross sections looks white after etching. Therefore, understanding the mechanism of white structure flaking is important for wind turbine gearbox reliability.

Flaking in rolling bearings occurs due to rolling contact fatigue and it is a similar phenomenon as spalling in gears. Flaking is generally classified to subsurface originated flaking, which is initiated at nonmetallic inclusions in materials and surface originated flaking, which occurs under contaminated or poor lubrication conditions [2]. However, recently white structure flaking can be seen in several applications, which is a different type of flaking from the subsurface and surface originated flaking mentioned above. For example, it is known that white structure flaking sometimes occurs in bearings for automotive electrical accessories as shown in Figure 1 [3]. There are many studies about the failure mechanism and the countermeasure for white structure flaking in automotive bearings. Some of them suggested that this type of flaking is induced by hydrogen generated by decomposition of the lubricating oil, grease, or water in the lubricant and that this phenomenon is concerned with hydrogen embrittlement [4] [5] [6] [7] [8] [9] [10] [11].

Axial cracks are also observed in failed bearings for wind turbine gear boxes [12]. This failure mode is very unique and it is seldom found in other applications. The same microstructural change as seen in white structure flaking is often observed in the cross sections around the axial cracks. However, it is unclear whether the mechanisms of white structure flaking and axial cracking are the same or not. In this study, rolling contact fatigue tests were performed in order to reproduce white structure flaking and axial cracking by using specimens charged with hydrogen. From the view of hydrogen theory, influ-

encing factors in operating conditions were discussed and effects of materials on bearing life were suggested as the countermeasure.

Observation results of failed bearings for wind turbine gearboxes

Failed bearings used in wind turbine gearboxes have been observed and two types of failures were mainly observed, which are classified as white structure flaking and axial cracking.

Figure 2 shows the observation results of a failed cylindrical roller bearing, which were used on the high speed shaft in wind turbine gearboxes. A small flaking was seen in the raceway surface as shown in Figure 2a. Figure 2b shows the cross section of the

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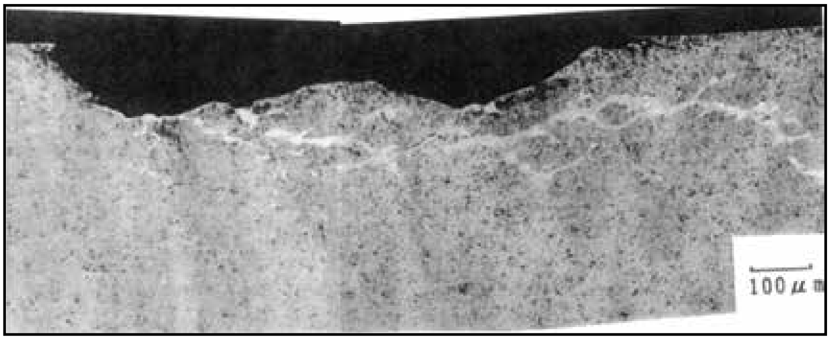

Figure 1: An example of the cross section of white structure flaking in an automotive electrical accessory bearing [3]

flaking area at the dotted line in Figure 2a. A microstructural change called white structure was observed at the flaking. Flaking morphology of failed bearings in wind turbine gearbox and automotive electrical accessories seem to be very similar as shown in Figure 1 and Figure 2b although bearing types and size are quite different. Namely, small size ball bearings are used for automotive electrical accessory and large size roller bearings are used for wind turbine gearboxes. Figure 2c shows the cross section of an area without flaking in the same bearing as shown in Figures 2a and 2b. White structure was observed even in this area, which is most likely to be the prior stage to flaking. Therefore it is presumed that this type of flaking in wind turbine gearboxes is initiated at the white structure.

Figure 3 shows the observation results of the other failed bearing, which is also a cylindrical roller bearing and used on the high speed shaft in wind turbine gearboxes. There were several large cracks longer than 10 mm and many small cracks around 1-3 mm in the axial direction on the raceway surface of the inner ring. Figure 3a shows two small cracks chosen of many axial cracks, which were observed on the raceway surface. The small cracks seem to be an early stage of crack propagation. A small axial crack was chosen for the cross section observation because small cracks


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are easier than large cracks to find the location of the crack initiation. Figure 3b shows the cross section including the small axial crack area. White structure was seen and it is seemed that a crack propagated along the white structure and reached the raceway surface. This crack is seen as the axial crack on the raceway surface.

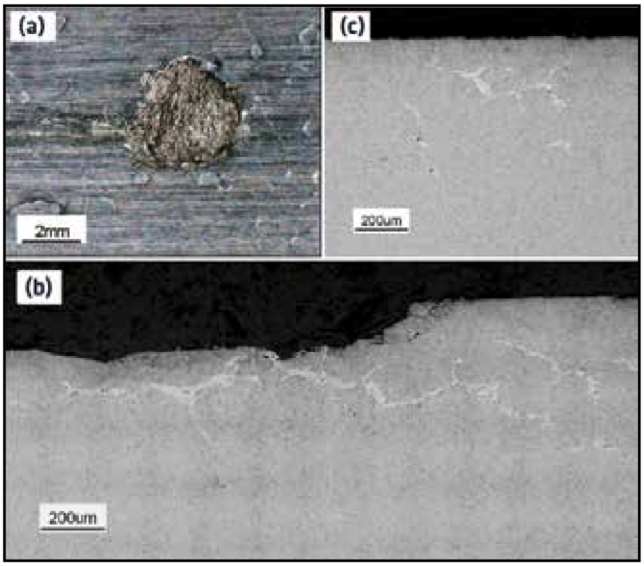

Figure 2: The raceway and the cross section of a failed bearing with white structure. a) Raceway surface of flaking area b) Cross section of the dotted line in Figure 2a c) Cross section of no flaking area

Rolling contact fatigue tests to reproduce white structure flaking and axial cracking

Reproduction of the bearing failure mode is important to know the failure mechanism and to find the most appropriate countermeasure. We carried out two kinds of rolling contact fatigue tests in order to reproduce white structure flaking and the axial cracks. Hydrogen is utilized in these tests because microstructural changes called white structure were seen in both of these failure modes.

Experiment to Reproduce White Structure Flaking

Flat disk type specimens with a diameter of 65 mm and a thickness of 6 mm were used in rolling contact fatigue test. The specimens were made of JIS-SUJ2 bearing steel, equivalent to SAE52100 and DIN-100Cr6. The specimens were quenched and tempered to produce a final hardness of 740 HV and the surface was ground and then lapped.

Before rolling contact fatigue testing, the specimens were charged with hydrogen by immersing them inNH4SCN aqueous solution at 323 K for 24 h.

The specimens were immediately assembled into the thrust bearing test machine after having been charged with hydrogen as shown in Figure 4. The upper race was a 51305 thrust bearing ring and the lower race was the specimen mentioned above. The rolling elements were 6 balls with a diameter of 9.525 mm. The retainer used was made of brass. The lubricating oil used was ISO-VG68. The maximum contact pressure was 3.8 GPa and the rotating speed was 1000 min-1.

Test Result of Rolling Contact Fatigue to Reproduce White Structure Flaking

Figure 5 shows the result of thrust type rolling contact fatigue tests using the hydrogen-charged specimen and uncharged specimen. Flaking occurred in the hydrogen-charged specimens, and the rolling contact fatigue life was much shorter than in the uncharged specimen.

Figure 6a shows the microstructure of the flaking cross section in the hydrogen-charged specimen. White structure was observed around the flaking area. White structure was observed also in the cross section of an area without flaking as shown in Figure 6b. Therefore, it is presumed that this flaking was initiated from white structure formed subsurface. On the other hand, flaking did not occur and the tests were suspended in the uncharged specimen. There was no microstructural change in the uncharged specimen. Therefore, it is presumed that hydrogen induced microstructural change and decreased rolling contact fatigue life.

It seems that these microstructural changes observed in the rolling contact fatigue tests using hydrogen- charged specimens are the same microstructure as seen in failed bearings of wind turbine gearboxes and automotive electrical accessories. It is reported that hydrogen enhances localized plasticity and this mechanism is known as the HELP theory [13]. Therefore, it is supposed that white structure represents a local-

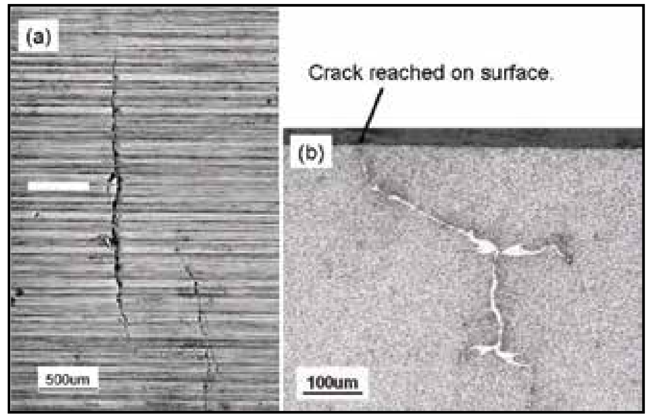

Figure 3: The raceway surface and the cross section of a failed bearing with axial cracks. a) Axial cracks on the raceway surface b) The cross section through the cracks

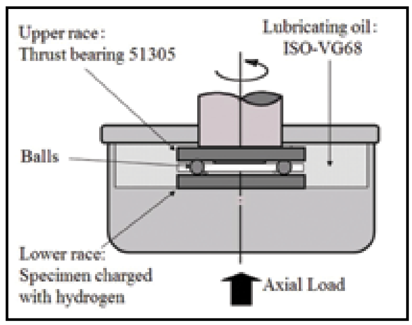

Figure 4: Schematic of the thrust type rolling contact fatigue test machine

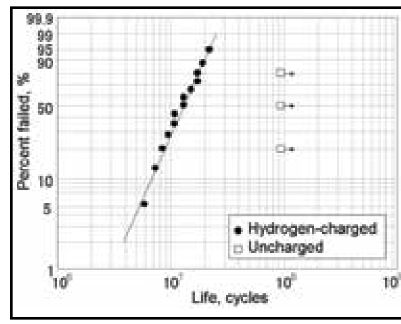

Figure 5: The results of thrust type rolling contact fatigue tests

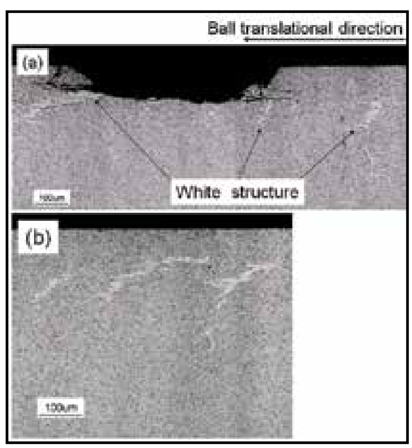

Figure 6: The cross section of hydrogen-charged specimen a) Flaking area b) No flaking area

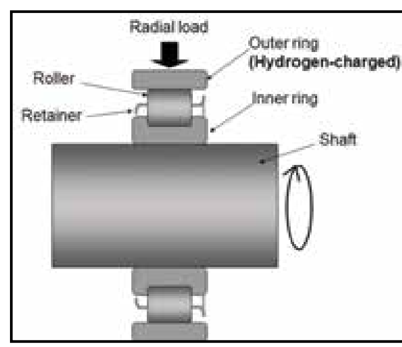

Figure 7: A schematic of radial type bearing test machine

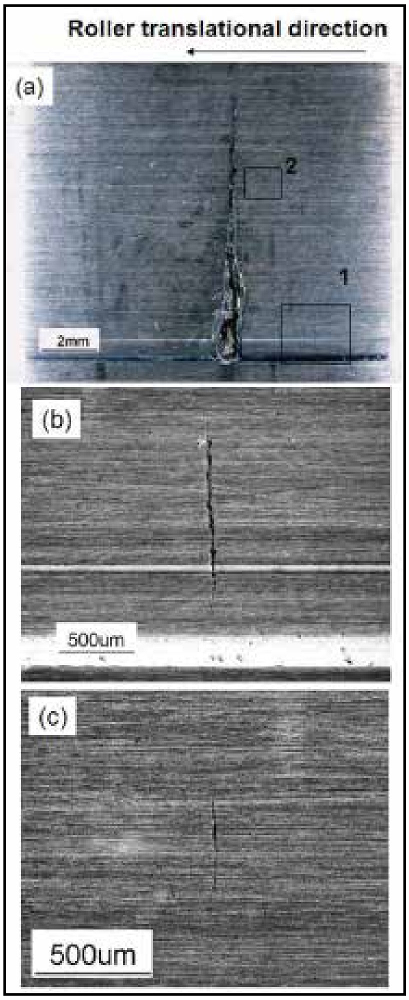

Figure 8: The raceway surface of the hydrogen-charged outer ring a) Large axial crack b) Magnification of position 1 in Figure 8a c) Magnification of position 2

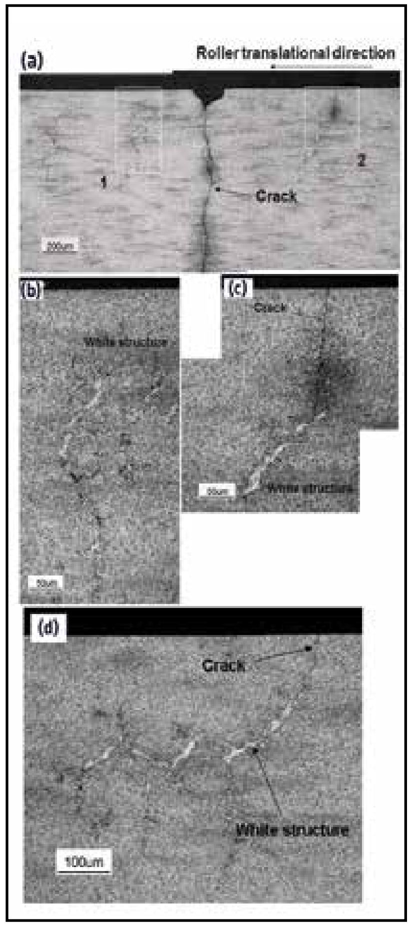

Figure 9: The cross section of the cracked area of a hydrogen-charged outer ring a) The cross section of position 2 in Figure 8a; b) Magnification of position 1 in Figure 9a; c) Magnification of position 2 in Figure 9a; d) The cross section of the small crack in Figure 8b

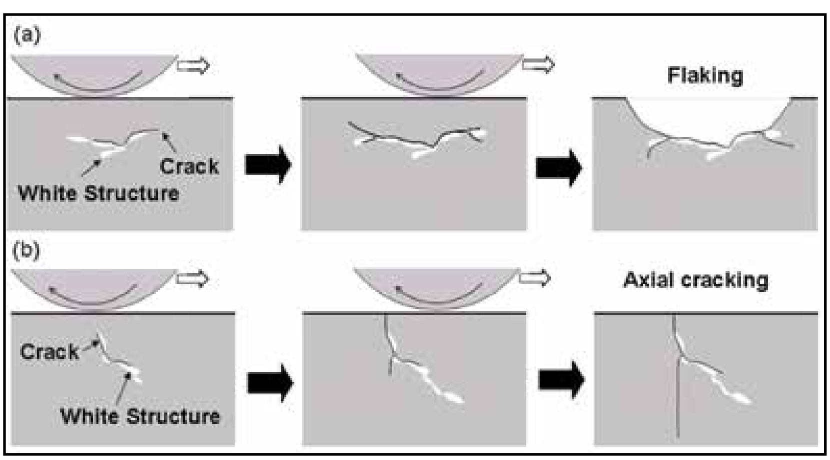

Figure 10: Schematics of the failure process of white structure flaking and axial cracking a) The case of flaking b) The case of axial cracking

ized microstructural change by interaction between cyclic plasticity and hydrogen in the rolling contact fatigue process [11].

Experiment to Reproduce the Axial Cracks

Cylindrical roller bearings are used for the experiment to reproduce the axial cracks, because they are often used for wind turbine gearboxes and the axial cracks have not been seen in ball bearings. Although, white structure flaking has been observed in ball bearings. Bearing number of N308 made of JIS-SUJ2 bearing steel, equivalent to SAE 52100, were used as the test bearings with a bore diameter of 40 mm and an outside diameter of 90 mm. Only the outer ring was separated and charged with hydrogen by the same method mentioned previously and the inner ring and the rollers were uncharged, and then the test bearing was set on the radial type bearing test machine as shown in Figure 7. The reason why the outer ring was chosen for hydrogen charge is that hydrogen in the outer ring is more difficult to diffuse out of the steel than the inner ring as the temperature of outer rings are normally lower than of inner rings. The lubricating oil used was ISO-VG150. The maximum contact pressure on the outer raceway was 2.1 GPa and the rotating speed was 3000 min-1.

Test Result of Bearing Life Test to Reproduce Axial Cracks

Bearing life test of the hydrogen-charged bearing was stopped by detecting the vibration at the testing time of 280 h. On the other hand, the test of the uncharged bearing was suspended at the testing time of more than 1000 h because there was no sign of bearing failure.

Figure 8 shows the outer ring raceway surface which was charged with hydrogen. One large crack and two small cracks were observed. These cracks propagated straight in the axial direction and were identical to the axial cracks in the failed bearings of wind turbine gearboxes.

Figure 9a shows the cross sections of the cracking area including the position 2 in Figure 8a. The large crack propagated in the depth direction. White structure was observed independently in Figure 9a position 1 to the left of the large crack magnified in Figure 9b. And also, Figure 9c is the magnification of the position 2 in Figure 9a and including the small axial crack

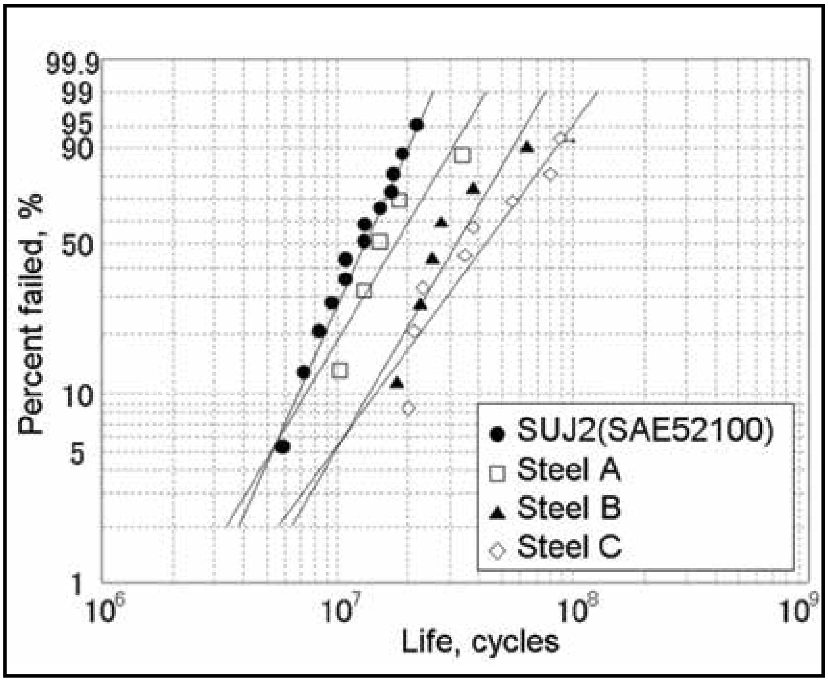

Figure 11: The effect of the chemical composition of steel on white structure flaking life

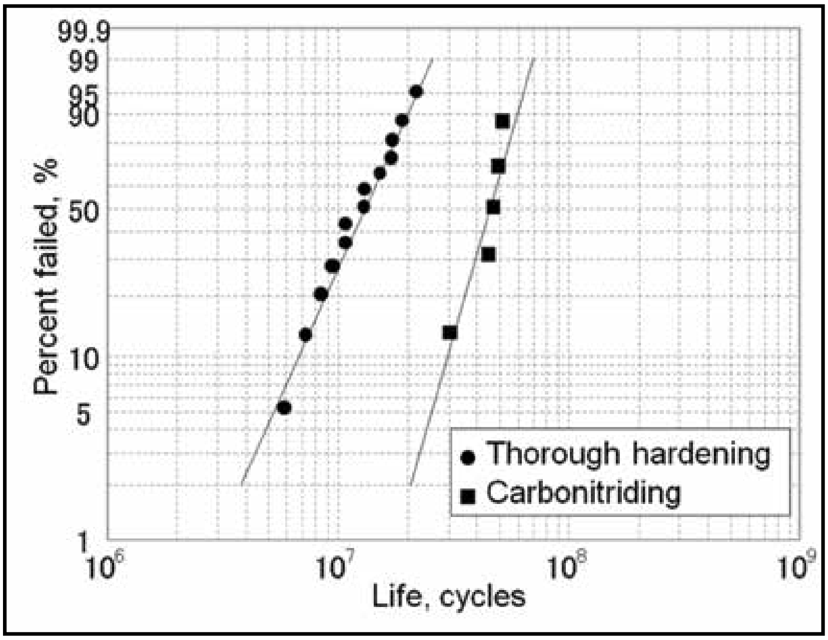

Figure 12: The effect of heat treatment on the white structure flaking life.

in Figure 8c. The small crack connected with white structure. Therefore it is supposed that white structure was formed first such as in Figure 9b and then a small crack initiated from the white structure and propagated to the raceway surface such as Figure 9c and finally the crack propagated in the axial and depth directions such as is visible in Figure 8a and Figure 9a. Figure 9d shows the cross section including the small axial crack in Figure 8b. White structure was observed also in this area and it seems that the crack initiated at the white structure and propagated to the surface.

However, white structure was not observed on the cross section of the large axial cracks. This reason is supposed that the initiation of the large axial crack would be white structure, but it is difficult to observe the cross section pinpointing the crack initiation. It is much easier to observe the cross section of the crack initiation in the small axial cracks.

Failure mode of the axial cracks is very unique and is seldom seen in other applications except for wind turbine gearboxes. However, it seems that the hydrogen-charge method does reproduce it. This method is very simple and the other effects on rolling contact fatigue are small. Therefore, it is supposed that axial cracks seen in wind turbine gearbox bearings are also caused by hydrogen. The patterns of white structure due to hydrogen are random, so that cracks along the white structure can propagate in various directions. It is supposed that some cracks mainly propagate in a horizontal direction to the rolling elements' translational direction and finally cause flaking, and that other cracks mainly grow in the vertical direction to the rolling element's translational direction and results in the axial cracks on the raceway surface as shown in Figure 10.

Operating condition inducing white structure flaking

The bearing failures in wind turbine gearboxes are more likely to be caused by hydrogen as shown in the rolling contact fatigue tests to reproduce white structure flaking and axial cracking. Therefore, it is important to know the causes of hydrogen generation and penetration into the bearing steel, although there is no direct evidence that hydrogen is generated and penetrated into the steel in wind turbine gearbox bearings. It is reported that hydrogen is generated by decomposition of lubricant and it is enhanced by the type of lubricant, water in the lubricant, slip, vibration, and electric current [3] [4] [5] [6] [7] [8] [9] [14]. These previous studies are mainly conducted for automotive bearings. However, influencing factors are basically common also to wind turbine gearbox bearings.

Type of Lubricant

It is reported that lubricant is decomposed by a chemical reaction with a fresh metal surface, which is formed by local metal-to-metal contact and thereby generates hydrogen [4] [5] [6] [7] [8] [9] [14]. Bearing life of white structure flaking is depending on additives included in the lubricant [4] [5] [8] [9] [14]. Some additives decrease bearing life and other additives increase it. The effect of extended life is more likely due to the oxidation film formed by a tribochemical reaction. Oxidation film can prevent a fresh metal surface from being exposed to lubricants and keeping the raceway surface chemically stable as some kinds

of additives enhance to form the oxidation film on the fresh metal surface.

Slip and Vibration

Slip between rings and rolling elements and bearing vibration can cause local metal-to-metal contact resulting in the exposure of a fresh metal surface. In the study about automotive ball bearings, it is reported that white structure was not formed at the bottom center of the raceway where maximum contact pressure was subjected, but instead near the raceway shoulders where large differential slip occurred [6] [7] [9].

Slip between rings and rollers are relatively small in cylindrical roller bearings and tapered roller bearings, which are normally used for wind turbine gearboxes. However large slip may occur during rapid acceleration and deceleration of a rotating shaft.

Electric Current

The problem of white structure was well known first in bearings for automotive electrical accessories. Static electricity was believed as the cause of hydrogen generation because frictional electrification can occur between the pulley and the drive belt made of rubber. It is reported that ceramic ball and an insulated pulley to shut out electric current prevented white structure flaking and that the grease containing nano-carbon powders with conductivity was also very effective because it can keep static electricity neutralizing and prevent the electric discharge at metal-to-metal contact [8]. Electric discharge forms a fresh metal surface where the steel surface is locally melted by a spark.

Electrical corrosion in rolling bearings only occasionally occurs in generators of wind turbines [1]. Stray currents from the generator may affect gearbox bearings.

Effects of material on white structure flaking

Hydrogen is most likely to be a concern with bearing failures in wind turbine gearboxes as mentioned previously. Prevention of hydrogen generation and penetration into the bearing steel is very effective countermeasures for white structure flaking; however it is currently unclear which operating conditions induce wind turbine gearbox white structure failures. Material improvement with a strong resistance to hydrogen is also a candidate as another countermeasure.

Effect of Chemical Composition of Steel

Figure 11 shows the result of a rolling contact fatigue test using the flat disk specimens charged with hydrogen and the thrust type rolling contact fatigue test machine in the same way as shown in Fig. 4. Four kinds of steels were used for the specimens; JIS-SUJ2 equivalent to SAE52100, steel A , B and C. Chemical compositions were different in them; steel A contains more Mn, steel B contains more Si and steel C contains more Cr. Rolling contact fatigue life of steel A, B and C were extended comparing to JIS- SUJ2. This result suggests that white structure flaking life can be extended by improvement of chemical composition of steel and it can delay formation of the white structure.

Effect of Heat Treatment

Figure 12 shows the result of a rolling contact fatigue test using hydrogen-charged specimens in the same way. Two kind of specimens with the same chemical composition of steel (JIS-SUJ2) and a different heat treatment were used, namely one data set used was through hardened specimens and the other was carbonitriding specimens. The rolling contact fatigue life of the carbonitriding specimens was longer than the through hardened specimens. It is supposed that compressive residual stress and larger amounts of retained austenite near the surface, which were formed by the carbonitriding heat treatment were effective against white structure flaking. Compressive residual stress can delay crack propagation initiated at the white structure, resulting in an extended time from crack initiation to flaking. Retained austenite can delay hydrogen from concentrating in high subsurface shear stress areas because the hydrogen diffusion rate in an austenitic structure is much slower than in a martensitic structure [15].

These results suggest that an optimum combination of chemical composition of the steel and heat treatment condition can produce long life bearings resistant to the formation of white structure flaking.

Conclusions

The following conclusions were obtained from investigating failed bearings in wind turbine gearboxes, conducting rolling contact fatigue tests to reproduce the failure modes, and estimating material effects on the flaking life.

1. Failure modes of wind turbine gearbox bearings were mainly

classified as white structure flaking and axial cracking on the raceway. Both of them were involving a microstructural change called white structure.
2. White structure flaking and the axial cracking were reproduced by using specimens charged with hydrogen in rolling contact fatigue tests. The axial cracks also seem to be initiated at the white structure. Therefore it is supposed that both failure modes in wind turbine gearbox bearings were caused by hydrogen.
3. Additives in lubricants, slip, vibration and electric current can induce hydrogen generation by decomposing lubricant and penetrating into the bearing steel, although there is no direct evidence of this in wind turbine gearbox bearings.
4. Improvement of the chemical composition of steel can extend the white structure flaking life and it is supposed that the suitable addition of the alloying elements delays the progression of microstructural change. Carbonitriding heat treatment was also effective against the formation of white structure flaking, because it is presumed that compressive residual stress near the surface can delay crack propagation and larger amounts of retained austenite can delay hydrogen concentration in areas of high shear stress.

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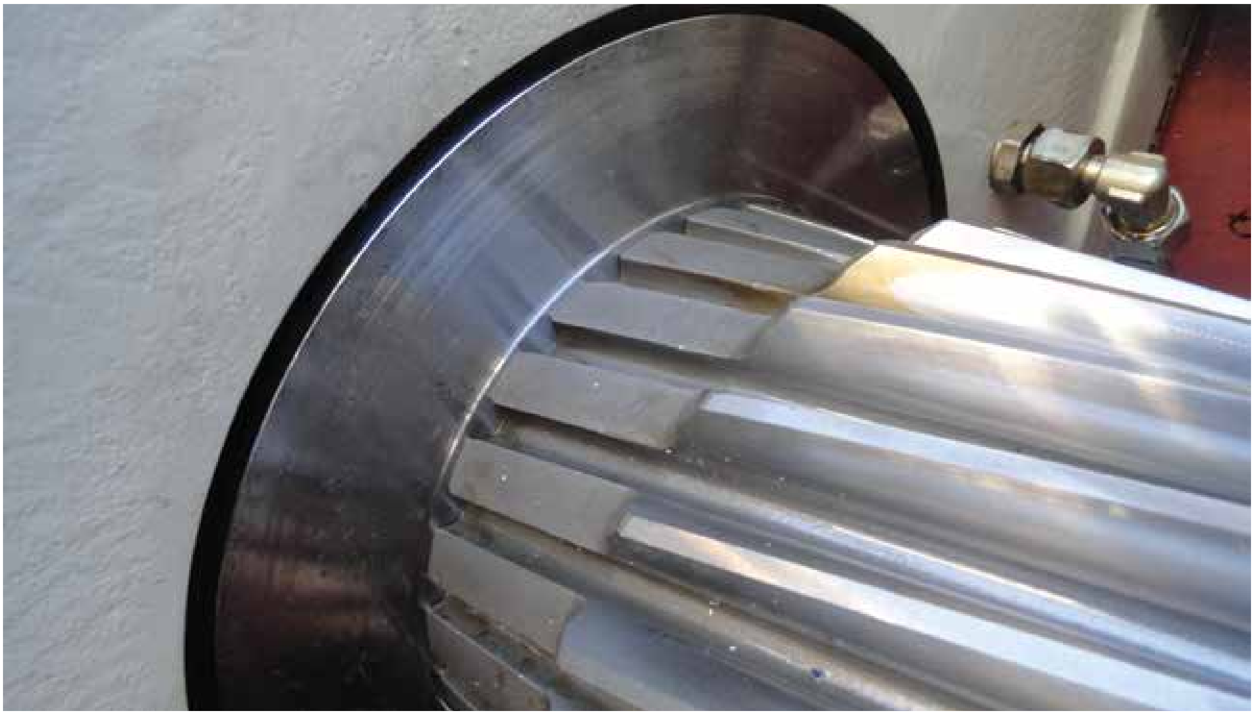
Selecting the right drivetrain inspection technology

By Andrew Engle
Availon Inc.



Vibration frequency analysis can be a powerful tool for diagnosing mechanical and electrical problems in wind turbine drive trains. However, it seems that some people are still skeptical about the accuracy of the technology. Perhaps those people have had bad experiences with vibration analysis in the past. Poor vibration analysis could yield false positives or worse, missing damage in a major component entirely. To avoid this situation some wind farm owners may rather perform a visual inspection via a bore scope camera. However, turbine owners may not realize that bore scope inspections have many limitations of their own. This article will review the two inspection types: vibration analysis and bore scope inspections.

Bore scope inspections have long been the go-to inspection technology for determining gearbox problems in the wind industry. Its biggest advantage is being able to capture pictures, which offer indisputable evidence of damage. However, these visual inspections are not cheap. Typically, if you are performing a full visual inspection of a gearbox it will take around six to eight hours to complete. Since there would need to be two technicians in the tower, this equals 12 to 16 labor hours that need to be compensated. Teams that gather vibration data need about two hours to complete their work, equaling a total of four man-hours. This option saves money and allows the vibration team to gather data from multiple towers in a day. The camera used with bore scope inspections has limited access to certain components. Depending on the gearbox type, a bore scope camera can generally only access around 90 percent of the gear teeth and only 30–40 percent of the bearing races and rollers. There are multiple reasons why gearbox bearings are difficult or not possible to inspect. Some of these reasons include:

- An oil dam plate could be installed in front of the bearing
- The bearing's cage is too close to the bearing race to allow camera access
- The bearing rollers are small and too close together for the camera to fit in-between
- The bearing is completely sealed off
- Large gears sit in front of the bearing, making it difficult to access

With vibration analysis, all gear teeth and bearings can be examined since it records the frequencies generated by all moving contact surfaces. This allows a more thorough inspection in about 30 percent of the time.

Borescope inspections on the generator and main bearings are not always

Photo taken during the up-tower gearbox repair to replace the intermediate speed shaft bearings.

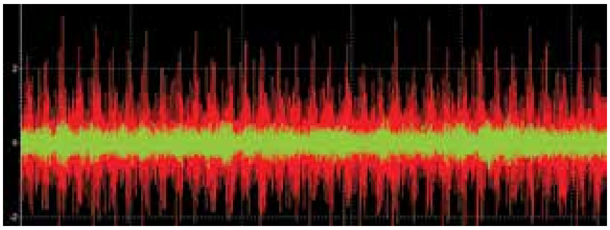
A picture of the damaged rotor side intermediate bearing inner race.

possible. Generator bearings and main bearings are usually packed with grease, and the bearing surfaces cannot be seen in this condition. Vibration analysis can easily pick up bearing fault frequencies in these components while also detecting other problems which cannot be detected during a visual inspection. These defects include blade unbalance, coupling misalignment, generator looseness, generator frame damage, generator stator and rotor electrical problems, and more.

While not dismissing the value of bore scope inspections, we highly recommend contacting Availon. Our engineers and technicians have vast experience in both—borescope inspections and vibration analysis—and can suggest the right technology for your particular application.

For example, we would recommend using the vibration analysis technology during End of Warranty inspections or when inspecting major components suspected to be damaged. Recently, Availon was contracted to perform end-of-warranty inspections on a wind farm of Vestas V80-1.8 MW turbines. As part of the scope of the inspection, vibration data was gathered from the wind turbine's drive train. During the analysis of the data it was found that one of the turbines had a large defect located on the inner race of the intermediate speed rotor side bearing in the gearbox. A bore scope inspection was attempted and an oil dam plate installed in front of the bearing prevented the inspectors from being able to access the inner race.

Although the bearing could not be visually inspected, the vibration data was enough evidence to claim the gearbox under the OEM's warranty. Shortly after finding the defective bearing an up-tower repair was ordered to replace the bearings on the intermediate speed shaft. During the gearbox repair the rotor side intermediate speed bearing was removed and the inner race found to be in very poor condition, just as the vibration analysis



Vibration waveform showing the intermediate speed bearing damage. The green signal shows the signal recorded from a good bearing. The red signal was recorded from the damaged bearing.

indicated. After two days the repair process was complete and the turbine returned to normal operation.

Due to the swiftness and accuracy of the vibration analysis, the owner of the wind farm was able to get a thorough drivetrain inspection at a low cost. If the owner had chosen to perform site-wide borescope inspections then the inspection cost would have been much higher and the damage bearing mentioned above would not have been found.

Let's be clear: This does not mean that there is no place for bore scope inspections. The most effective inspections are when vibration analysis and bore scope inspections are used together. The vibration analysis can be used to quickly locate and identify the problem while the bore scope can be used to gather visual evidence of the damage. This process is the perfect formula to get the most thorough inspection for the most economical price.

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UNDERSTANDING TURBINE SYSTEMS OPERATIONS AND ELECTRICAL SAFETY ARE ESSENTIAL TO ELECTRICAL TROUBLESHOOTING

By Jack Wallace
Frontier Pro Services

We spend lots of time performing electrical troubleshooting at a wind farm. Let's see if I can get you thinking about how you can improve your troubleshooting skills with a few tips and techniques.

To be a better troubleshooter, you should understand the theory of operation of your specific type of wind turbine. Understanding the specifics of your turbine's operation will allow you to understand when it is not operating properly. Besides the basic theory of operation (of which we covered in magazine in the February 2013 issue of *Wind Systems*), you should know the theory of operation for: the cooling system, heating system, pitch system, braking system, yaw system, converter system, and any other subsystem or component within your turbine. You should understand your control system as to which parameters are adjustable and which are not. And you should be asking why it is that way.

Secondly, you should have a good understanding of electrical safety and of your electrical test equipment. Your main troubleshooting tool for electricity is your digital multimeter. You should have a sound understanding of its capabilities and it limitations. You should know how to check for voltage, current, and continuity. It goes without saying that you should always follow proper safety procedures and use your protective and safety gear properly. Another tool you should know how to use is your turbine's electrical schematic. You should have knowledge of its specific protocols for identifying electrical components, how circuits continue from page to page, and how to identify the component and its location. The lines that indicate wires on your schematic may be short, but the actual wiring circuit could in fact run from down-tower to up-tower. If you are fairly new to the wind farm, you can probably gain some notes from your coworkers who have been on site for a while. A good technician will take time at the wind farm to get familiar with their specific equipment. These technicians will take the time to measure the resistance of that hydraulic solenoid valve and written its value of 450 ohms at its location on their schematic. He will have taken time to take a resistance reading of the windings of the yaw motor—recording this note to his troubleshooting notebook. He will know the value of the windings when it is connected in a wye connection and its individual winding values. You will know its resistive values between the windings and to ground. An experienced tech will know by testing what is an acceptable current draw value of every motor in the turbine. The information will be noted on his schematic or in his troubleshooting notebook. It is always smart to have handwritten diagrams and notes of a specific situation or holes dug for repairs. The same problem may show up again a year from now.

> ***"I would prefer my technicians to go out and look, listen, feel, and smell the turbines in the field during wind storms than to sit around the office catching up on paperwork."***

I would prefer my technicians to go out and look, listen, feel, and smell the turbines in the field during wind storms than to sit around the office catching up on paperwork. That's the best time to learn how your machines run and operate. This focused observation will be valuable as the turbines age.

When it comes to troubleshooting electrical systems, some technicians get overwhelmed, especially if they have not had any formal troubleshooting training to help build these skills. Here are some tips that will help them.

Most electrical circuits are built the same way. The electrical circuits have components that do work for us. The type of work we ask electricity to do for us comes down to this: we ask for motion through magnetics; we ask for light through resistance; and we ask for heat through resistance. So, there are magnetic loads such as solenoid coils, relay and contactor coils, and motors and generators. We get light and heat typically through resistive loads. (LEDs and logic are not included here).

In addition to the items that we have do work for us, we have conductors—which are the wires. The wires get larger as we ask them to move more current for us.

We also have switches. The switches can be manually activated like a light switch on the wall. A switch can be activated by hydraulic pressure, by a low temperature or high temperature. A switch can be activated by a counter or a tachometer. A limit switch is activated by something reaching a predetermined limit. A float switch is activated by a liquid level. A switch can be activated by a magnet as in a relay or contactor. You get the point. Many things can activate a switch.

No matter what, in an electrical circuit on a wind turbine, there will always be just one load per circuit. Period. Only one item per circuit will do the work such as a motor, coil or resistor. Each load has its own circuit.

In that same circuit with the load there could be one switch, or a million switches. The switches could be wired in series with one another or in parallel with each other, or a combination of series and parallel. But for each circuit there will only be one load. If you know the value of the load in ohms, you can quickly see if it is defective.

I hope the tips help.

Dingo Software

Since its first endeavor into wind energy in 2009, this Australian software company has become a leader in condition-based maintenance

By Stephen Sisk

There had to be a better way. Maintenance operations were stuck in a seemingly endless downward spiral of inefficiency. If allowed to continue-with this "it's broken, fix it" mentality, companies would stray further from their cost and production targets, eventually losing their competitive edge.

These were the thoughts that engineer Paul Higgins struggled with after observing industrial maintenance operations in the U.S. and Australia. The ages-old scheduled maintenance methods weren't cutting it. Resources—money, time, and materials—were being wasted.

In 1991, Higgins set out to try and revive maintenance operations with a new way of thinking—and Dingo Software was born. Originally, the company focused on the mining industry.

"One of our first projects was to develop an oil analysis software application for one of the largest global mining companies," said Colin Donnelly, director of product management for Dingo Software. "This software program was the first in a suite of applications designed to help the North American and Asia Pacific mining markets over the next ten years."

At that time, the company saw the need to expand its efforts into providing a complete condition monitoring system in order to take the fullest advantage of its maintenance software suite.

Ever since, Dingo has been committed to assisting its customers in taking a proactive, total asset health approach to maintenance.

The company first applied its approach to the wind industry in 2009, at the request of a leading turbine manufacturer.

"This OEM required a solution that could monitor the condition of gearboxes and hydraulic systems in all North American wind turbines under service contract (over 6,000 turbines)," Donnelly said. "These wind farms were located throughout the U.S. and Canada, using multiple regional lubrication laboratories. The Dingo solution was used to consolidate oil analysis information from all laboratories and then make it available to engineers and regional office service groups in a common platform, the Trakka® software and database, a powerful decision-making engine."

The challenge the manufacturer faced was the high expense of scheduled maintenance tasks—gearbox oil changes in particular—which in many cases were deemed unnecessary upon inspection.

Dingo Software's involvement in the wind industry has grown significantly since that initial contract. The company now monitors over 15 GW of wind energy assets in the U.S. and Canada.

The company's primary product and service offering for the wind energy industry is its Asset Wellness™ solution—a suite of tools used by both manufacturers and operators to provide an ongoing, proactive picture of asset "health."

The Asset Wellness suite includes:

- Trakka—a cloud-based predictive analytical and workflow maintenance management tool for almost any time-series data, used to analyze and store asset and component condition information for the purpose of providing the knowledge to make informed maintenance decisions.
- Condition Intelligence®—which proactively identifies issues with components and assets. Based on those assessments, the system provides the client with recommendations and action plans to correct the problems in an appropriate time frame. This removes the need for customers to have condition monitoring experts on staff, as Dingo provides the analysis of the data and distill down to the action required of technicians in the field
- Workflow Management—to successfully manage the health of wind turbines requires not only the management of the condition monitoring data, but also the management of all maintenance actions that stem from this data. Trakka's workflow management can integrate with the customers ERP system (SAP etc.) to provide a current status view of all maintenance actions. These actions are monitored past the paperwork stage (being recorded as complete)—and are only resolved once the condition of the equipment returns to a normal operating state.
- Fleet Analysis—Trakka's group trending capability allows for analysis and comparison of both individual units and entire fleets of turbines. It can tell which gearbox types are wearing the least, which oil

type is performing the best, and other analysis of specific fleet problems or concerns.

Using the Asset Wellness solution, Donnelly said, allows operators to "make a seamless transition from the OEM and proactively manage the health and cost of their fleet."

Specific examples of how this is achieved include:

- providing the information needed to maintain and prolong asset lifespan beyond the end-of-warranty period
- assisting operators in making the transition from traditional planned maintenance practices to condition-based maintenance methods (through the use of additional data sources and Trakka)
- offering a comprehensive review of the data, allowing for more informed decision-making
- maximizing the amount and value of information that is retrieved from a tower climb, potentially lessening the need for subsequent climbs

At the heart of its business—whether in the wind industry, mining, oil and gas, or rail—is Dingo's commitment to its three core values—hard work, caring, and results.

"We take these values very seriously and practice what we preach," Donnelly said. "We care about each and every one of our customers and work hard to help them achieve their goals and drive results. At Dingo, the definition of winning is 'Creating Wins for our Customers.' "

Dingo finds value in building and maintaining relationships with those customers because the company understands the value of word-of-mouth testimony about its products and services. Much of its business, Donnelly said, is based on peer recommendations.

"In order to provide each one of our customers with the highest level of service, we take the time to understand their specific goals and challenges and then tailor our approach to deliver the greatest benefit."

A greater overall benefit is the result of an outcome-based approach, Donnelly said, and has been the driving force behind the success that Dingo has enjoyed in a relatively short period of time in the industry.

"Unlike most companies who provide software or services in the condition monitoring and data management space, we decided to focus on asset health," Donnelly said. "Instead of being data focused, we are outcome focused. If our customers aren't improving on their cost and/or reliability metrics, then we aren't being successful."

Dingo Software is based in Brisbane, Australia. In addition to its corporate headquarters, Dingo has an office in Perth, Australia, as well as two North American offices.

Pat Shannon
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ITW WindGroup

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> *We've streamlined our approach to the market while providing a single point of contact to the market.*

How long has ITW WindGroup been operating in the wind energy industry? What was its genesis?

The ITW WindGroup was formed five years ago, combining the global resources of the divisions of ITW while providing a single entity as the point of contact. We've streamlined our approach to the market while providing a single point of contact to the market. Many ITW divisions have been supplying the industry since the inception.

What segments of the utility-scale wind energy industry does ITW WindGroup serve?

We've broken the industry into three segments: Foundation & Construction, Composites, and Operations & Maintenance.

In working with wind energy customers, what are their primary needs and how does ITW WindGroup go about meeting those needs?

The ITW WindGroup provides technologically advanced solutions to the industry based on customer pain points; their needs are as diverse as our product offerings. We're often on a jack up barge, in a blade production facility, or up tower working with the customer providing off the shelf solutions around their needs. If customization is needed, we rely on one of our many technical centers in Asia, Europe, or North America to truly add value to our customers.

With regard to maintenance, could you give us a general overview of the product offerings?

Our product offerings include: sealants, foundation repair materials, adhesives, anti-corrosion solutions, coatings, and cleaners. Truly, there are too many to list. Basically, we are a single entity who can provide most anything to build, install, and maintain a complete wind turbine from the foundation to the blade tip.

How does ITW WindGroup fit and operate within the larger corporate structure of Illinois Tool Works?

The ITW WindGroup is a division of the Polymers & Fluids group which is a $2 billion segment of ITW. The WindGroup is focused exclusively on the wind energy market relying upon the resources of all the ITW segments. We operate as a decentralized division with a strong entrepreneurial culture and a unique approach of customer fueled innovation.

How does the strength of being part of ITW benefit the wind energy consumer?

We have over 10,000 active patents within ITW with a host of engineering and scientific resources throughout the world. We bring our products close to the customer through global manufacturing with the technical and commercial resources that this industry demands. We can develop an innovative solution to a specific customer pain point, manufacture the solution from multiple manufacturing sites, and simultaneously roll out, support, and supply from most anywhere in the world.

Geographically, what markets does ITW WindGroup serve?

The ITW WindGroup has strategic operations and manufacturing sites located in North and South America, Europe, Asia, and India.

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CAN WE AFFORD STORAGE?

A dynamic net energy analysis of renewable electricity generation supported by energy storage

By Michael Carbajales-Dale,[*a] Charles J. Barnhart,[a] and Sally M. Benson[b]*

Introduction

Global energy demand is expected to nearly double by 2050.[1] To achieve this demand and avoid further exacerbating human-induced climate change, society must draw increasingly from affordable, accessible, sustainable and low-carbon energy sources.[2] Wind and solar resources are both renewable and abundant; however they are both weather-dependent, requiring techniques to mitigate their variable output.[3–5]

Global wind power and photovoltaic (PV) installed capacities are growing at very high rates (20% per year and 60% per year, respectively).[6–12] These technologies require large 'up-front' energetic investment. As these industries grow, some proportion of their electrical output is offset by the need to support manufacture and deployment of new capacity. The PV industry is currently operating at close to the *breakeven threshold.*[6] At this threshold, the *fractional reinvestment*[6] is 100%, i.e. the electricity produced by installed PV systems is equal to the energy required to manufacture and install new PV capacity. While this is manageable when PV provides only a small fraction of global electricity supply, it is imperative that the fractional reinvestment decreases as PV penetration rates increase.

While today both wind and PV provide a net energy surplus to society, their variable and intermittent nature requires increased flexibility in electricity grids.[3] A number of flexibility options exist to balance the electricity supply and demand: resource curtailment, flexible back-up generation, demand response and grid-scale electricity storage. Many of these techniques and technologies that increase grid flexibility also incur additional energetic costs.

The curtailment of wind and PV is often viewed as an undesirable loss of 'cost-free' and emission-free energy.[13] The demand response is seen as an integral feature of the 'grid of the future'. The specific technologies and techniques are numerous and evolving rapidly. For example, the amount of peak-power demand reduction that can be achieved through demand-side management, or the use of appliances with sensors and controls that dictate their time of use, remains uncertain.[14] Previous studies have explored the energetic costs and greenhouse gas (GHG) emissions associated with hybrid wind–PV–diesel systems.[15,16]

The present study analyses the industry-level energetic cost of deploying wind power and solar PV supported (backed-up) by grid-scale energy storage, thus converting an intermittent energy resource into a firm source of electric power. We use data on energetic costs to determine the additional burden placed on the wind and PV industries by concurrently building up storage capacity in order to mitigate variability and intermittency. We explore a range of cases, up to the extreme case where it is possible to supply up to three days of average power output from the renewable generator.

Net Energy Trajectories

Previous work presented net energy trajectories of each of the major PV technologies for the period 2000–2010.[6] The metric of interest for this framework was the *fractional re-investment, i.e.* what proportion of the gross electricity output of the industry is consumed in manufacturing and deploying new capacity. The net energy trajectories for PV technologies, single-crystal (sc-), multi-crystalline (mc-), amorphous (a-) and ribbon silicon (Si), cadmium telluride (CdTe), and copper indium gallium (di) selenide (CIGS), have been updated to 2012, with new data presented herein. Net energy trajectories have also been developed for wind technologies, on-shore and off-shore. The framework has also been adapted and expanded to explore the impact of storage deployment.

Determining the fractional re-investment of an energy production industry requires (1) knowledge of the energetic cost per unit of installed capacity [kWh_e/W_p], (2) the growth rate of the industry [% per year], and (3) the electricity output per unit of installed capacity [kWh_e/W_p/year] defined by the *capacity factor.* The following sections outline these data for the wind and PV industries.

Wind and PV Industry Growth Rates

The installed capacity of both wind and PV grew rapidly between 2000 and 2012.[6–12] The wind industry averaged growth rates of 20–40% per year. The PV industry grew even more quickly, between 20 and 70% per year. A referenced and detailed breakdown of growth rates and installed capacity, disaggregated by technology, can be found in the ESI.†

Energy inputs to energy and storage technologies

Life cycle assessment (LCA) and net energy analysis (NEA) studies have begun to build an understanding of the material and energetic requirements of production pathways for both electricity generation and electrical energy storage technologies. Meta-analyses of full life-cycle energetic inputs to PV[6], wind[17] and storage[18] technologies have been used. The distributions in these estimates are presented in Fig. S1 and S2 in the ESI.†

- Energy inputs to PV—We use data for energetic inputs to PV system production from a previous study.[6] The metric of interest was the *cumulative electricity demand* (CE_eD), defined as the amount of energy 'consumed' during the life cycle of a product or a service *expressed as electrical energy* equivalents. CdTe has the lowest median CE_eD, followed by ribbon silicon, mc-Si, CIGS, a-Si and finally, sc-Si. The study also presented a learning curve model to track changes in CEeD over time. Details of the learning model and learning rates are presented in the ESI.† Learning rates of between 13 and 20% were found for CE_eD of PV.
- Energy inputs to wind—Meta-analyses of energetic inputs to the wind turbine life-cycle have been conducted by a number of studies, the results being presented as either *energy intensity*[19] (ε), primary energy inputs per unit of electricity production [$kWh_{p,in}/kWh_{e,out}$]; *energy return on investment*[20] (EROI), electricity production per unit of primary energy input [$kWh_{e,out}/kWh_{p,in}$], i.e. 1/E or CE_eD.[17] On-shore technologies have a lower CE_eD per unit of nameplate capacity [kWh_e/W_p], however, off-shore technologies have slightly lower CE_eD on a per unit of output basis [kWh_e/kWh_e] due to their higher capacity factor.[17]
- ***Energy inputs to storage technology***—Life cycle assessment (LCA) data on the energetic requirements of manufacturing and deploying storage technologies have been assembled in two previous studies.[18,21] The first study showed that geological storage technologies, including compressed air energy storage (CAES) and pumped-hydroelectric storage (PHS), are over a factor of 10 less energy intensive (on a per unit storage capacity basis) than battery technologies.[18] Within the battery technologies, lead-acid (PbA) was found to be the least energy intensive, followed by lithium-ion (Li-ion), sodium–sulphur (NaS), zinc–bromine (ZnBr) and finally vanadium-redox (VRB). The first study employed data measured in terms of *primary energy equivalents*. The second study converted those data into *electrical energy equivalents*, including a discussion on the issues concerning conversion of inputs from primary to electrical energy equivalents.[21] These issues are also discussed in the ESI† for the present study. Since the common 'currency' in this analysis is electricity we utilize data from the second study.

Capacity Factor for PV and Wind

We here define the capacity factor as the *average power output of a technology relative to its nameplate capacity* [W_{avg}/W_p]. The average capacity factor for PV is around 12%, *i.e.* 1 W_p of installed capacity will generate 1 kWh_e per year.[6] We conducted a similar analysis for global wind installations and found the average capacity factor of the installed fleet of wind turbines to be around 25%, such that each W_p capacity of wind will generate 2.2 kWh_e per year. The datasets used did not distinguish between on-shore and off-shore technologies. The distribution in capacity factors is shown in Fig. 1.

Methodology

The methodology used in this analysis is an extension of the method used in a previous study[6] to include both the wind industry and also grid-scale energy storage. A number of scenarios for the deployment of storage technology mixes required to 'back-up' the PV and wind capacity have been explored: geologic storage only, battery storage only or a mix of all storage technology types. The main objective is to explore the impact of building up storage technologies on the net energy production from wind and PV assuming that the wind and PV industries must 'pay' the energetic costs of storage deployment.

We assume that in each time period τ [h], a generation technology is supplied with enough energy (either wind or sunlight) to deliver τ hours of average electrical power output. For

† Electronic supplementary information (ESI) available: Data on wind and PV installed capacity, capacity factors, and energetic cost; energetic cost data for storage technologies; details on methodology including derivation of storage requirements. ESI available at http://www.rsc.org/suppdata/ee/c3/c3ee42125b/c3ee42125b1.pdf

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example, in the case where $\tau = 24$ h, and using the capacity factors from the previous section (25% for wind and 11.5% for PV), the generation technology would produce $0.25 \times 24 = 6\ Wh_e/W_p$/day for wind and $0.12 \times 24 = 2.76\ Wh_e/W_p$/day for PV.

In a 'worst-case' scenario this energy supply would arrive in one period of time $t = \kappa\tau$, *i.e.* a block of 6 hours in the case of wind, at the rated capacity of the generation, i.e. $1\ W_e/W_p$. Since a steady supply of $0.25\ W_e/W_p$ is being delivered to the grid, the remaining $0.75\ W_e/W_p$ must be stored, requiring a total storage capacity of $0.75 \times 6 = 4.5\ Wh_s/W_p$/day for wind technologies.

When the generation is no longer supplying electricity directly, the storage is called upon to deliver electricity to the grid. In general, we may say that the amount of storage required per unit of capacity E_s/W_p to back up the generation for τ hours is:

$$\frac{E_s}{W_p} = \frac{\tau}{D}\kappa(1-\kappa) \qquad (1)$$

where D is the depth of discharge and κ is the capacity factor. For details on the derivation of this equation, see ESI† Section *Storage requirement*. In the following analysis, we assume that D = 100%. We also did not consider the need to increase the size of storage due to efficiency losses. By including such losses, the storage would either deliver electricity at a lower rate, ηW_{avg}, where η is the *round-trip efficiency*, for the full time $\tau - t$, or deliver electricity at the rate W_{avg} for a shorter time $\eta(\tau - t)$. The effects of these assumptions are discussed in greater detail in the Conclusion and in the ESI.†

We considered scenarios up to three continuous days without generation as an extreme example for purposes of illustration, since distribution in weather systems may entail three days without wind generation.[22] It should be noted that we do not thereby suggest that three days is the required level of storage to support wind and PV.

The amount of storage required to supply the average power output from the generation technology for the period that no generation occurs is explored more deeply in ESI† Section *Storage requirement*. Data and more details on the full methodology can also be found in the ESI.†

Results

Net energy trajectories for wind and PV

The learning model6 has been adopted to determine changes in CE_eD for wind technology. Only slight trends in CE_eD could be determined for the data, finding a learning rate of 4%. A learning rate of 4% means that each doubling in cumulative production brings about a 4% reduction in production costs, *i.e.* the cost of producing the 100th GW of installed capacity is 4% less than producing the 50th GW of installed capacity.

These curves and learning rates for CE_eD of PV[6] have been used to produce net energy trajectories for each of the wind and PV technologies shown in Fig. 2 (details on derivation and how to read these plots are presented in ESI† Section *EPBT* and *industry growth*). The horizontal axes display the CE_eD [kWh_e/W_p] on the top axis and energy payback times (EPBT) [years] for the median capacity factor of a given technology (i.e. 25% for wind and 11.5% for PV) on the bottom axis. The relationship between these two axes is dependent on the capacity factor. We have assumed here that both on-shore and off-shore wind technologies achieve the same capacity factors. In reality, off-shore wind often achieves capacity factors greater than 35%.[23]

The vertical axis represents the annual growth rate in installed capacity [% per year]. Diagonally sloping lines represent the fractional re-investment, i.e. how much of the gross electricity production of the industry is consumed in fueling its own growth. A fractional re-investment of greater than 100% (red region) means that the industry consumes more electricity than it produces on an annual basis, i.e. running an *energy deficit*. The

HEADLINES

Greensmith on track to integrate four new battery types in 2014

Greensmith, a leader in grid-scale energy storage technologies has announced it is on track to successfully integrate an additional four new battery types in 2014, bringing the company's total since inception to 12 using its battery-agnostic technology platform, now in its fourth generation. With over 23 MW of energy storage capacity to be deployed in 2014, Greensmith continues its rapid growth by serving an expanding list of strategic customers and channel partners looking to take full advantage of the company's proven technologies and application expertise, including frequency regulation, grid stability/deferral, renewable integration, and commercial/industrial functionality.

Refined over many years of development, innovation, and real-world deployment experience, Greensmith's software platform enables the rapid economic integration of both current and future battery technologies, always selected and configured according to the objectives and requirements of the target application. Although the company continues to develop and deliver turn-key energy storage systems at scale, a number of customers and partners are choosing to license Greensmith's software and integration technology a-la-carte.

"From the very start, Greensmith believed that the potential for energy storage lay beyond 'batteries-in-a-box,' and that robust layers of software, integration and optimization were critical to capturing its full value", said John Jung, Greensmith CEO. "It was also clear that a variety of battery alternatives, suitable for different application needs, would be available over time and therefore need to be easily integrated into a single, resilient technology architecture. So we built and advanced our battery-agnostic technology through multiple cycles of product development and delivery. We're quite pleased to be on pace to successfully integrate our 12th battery type by the end of 2014—and while it's become fashionable to proclaim battery-agnosticism in the marketplace, it's quite another thing to have actually executed and delivered the goods."

green region represents an *energy surplus*. For example, a fractional re-investment of 50% means that half of the electrical output of the industry is consumed in the growth of the industry, the other half being available to society.

The first point to note from Fig. 2 is that since 1994 the wind industry has been a net electricity producer. The CE_eD of on-shore wind is lower than off-shore wind. The growth rate in on-shore is also slower, leading to a lower fractional re-investment of around 5–10% in 2012 as compared with a value of 10–20% for off-shore in the same year.

Comparing wind with PV, we can see that PV technologies have both higher CE_eD and (due to their lower capacity factor) considerably longer EPBT than wind. The growth rates are also higher (up to 120% in the case of CIGS), such that the rates of fractional re-investment in 2012 were much higher for PV than for wind, anywhere between 20 and 150% depending on the technology.

CE_eD for generation–storage combinations

As demonstrated in ESI† Section *Storage requirement,* the maximum amount of storage necessary to supply one day of generation at an average power output is 4.5 Wh_s/W_p for wind and 2.4 Wh_s/W_p for PV. The difference is mainly due to the lower capacity factor of PV meaning that the average power output is assumed to be less than half that of wind.

We now include the energetic cost of deploying storage to support wind and PV technologies. The energetic cost includes only the deployment of storage and not energy losses associated with its operation. The 'up-front' energetic cost also does not include replacement for storage technologies that have lifetimes shorter than the generation technology. The energetic cost of deploying storage is dependent on the technology mix: geologic storage – 0.026 kWh_e/Wh_s; electrochemical storage—0.153 kWh_e/Wh_s and a mix of all storage types—0.117 kWh_e/Wh_s. Additional information on the methodology of the inclusion of energetic costs of storage can be found in ESI† Section *Deployment of storage*.

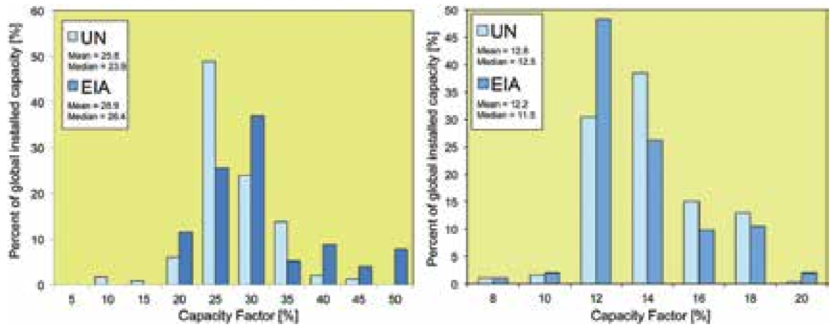

Fig. 1: Distribution in capacity factors [%] for the global installed capacity of wind (left) and PV (right – adapted from ref. 6) compiled using data for years 2008–2010.[7,8] The average capacity factor of wind is between 23 and 29%. The average capacity factor for PV is between 11 and 13%.

The net energy trajectory diagrams have been amended to depict the additional energetic cost of storage in Fig. 3. Shaded regions spread out from the 2012 marker for each generation technology bound by the constant growth rate (horizontal line) or constant fractional re-investment rate (diagonal sloping line), ***i.e.*** at a reduced growth rate, for the storage requirement to back up 12, 24, 36 and 72 hours of the average power output from the generation device (a value of 13.5 Wh_s/W_p for wind and 6.84 Wh_s/W_p for PV) using an equal mix of all of the different storage technologies, ***i.e.*** an average cost of storage of 0.117 kWh_e/Wh_s (see ESI† Section *Deployment of storage*).

Most PV technologies can afford up to 24 hours of the equal storage mix. The exceptions are sc-Si and CIGS, both of which are already operating at an energy deficit, the latter is mainly due to its current, very rapid growth rate (>100% per year). This suggests that PV systems could be deployed with enough storage to back up the natural day–night cycle and the PV industry could still operate at a surplus, supplying a net electricity yield to society even after accounting the electricity required to deploy new generation and storage capacity. The wind industry can support up to 72 hours of storage back up while still operating at an energy surplus. This suggests that the industry could deploy enough storage to cope with 3 day lulls in wind, common to many weather systems,[22] and still provide net electricity to society.

In Fig. 4 we see the impact of deploying different storage technologies with wind (left) and PV (right). Again, shaded regions spread out from the 2012 marker for each generation technology up to the additional cost of deploying 72 hours of storage back up using either geologic storage (pumped-hydro or compressed air), an equal mix of all storage types or only battery technologies.

Requiring the wind industry to deploy 13.5 Wh_s/W_p of electrochemical storage per unit of capacity installed (enough to provide 72 hours of back-up) would increase the CE_eD of off-shore wind to 2.9 kWh_e/W_p, meaning that, if the growth rate remained at 33% per year, the fractional re-investment would increase from 10–20% up to 40–60%. Alternatively, the growth rate would need to decrease to around 10% per year to maintain the same rate of fractional re-investment. A similar pattern emerges for on-shore wind. Even deploying enough storage to supply three days without generation using electrochemical storage does not cause the industry to run a net electricity deficit.

For PV, shown in Fig. 3, the same is not true. Some PV technologies (CIGS and sc-Si) are barely in the electricity surplus region, so the requirement of

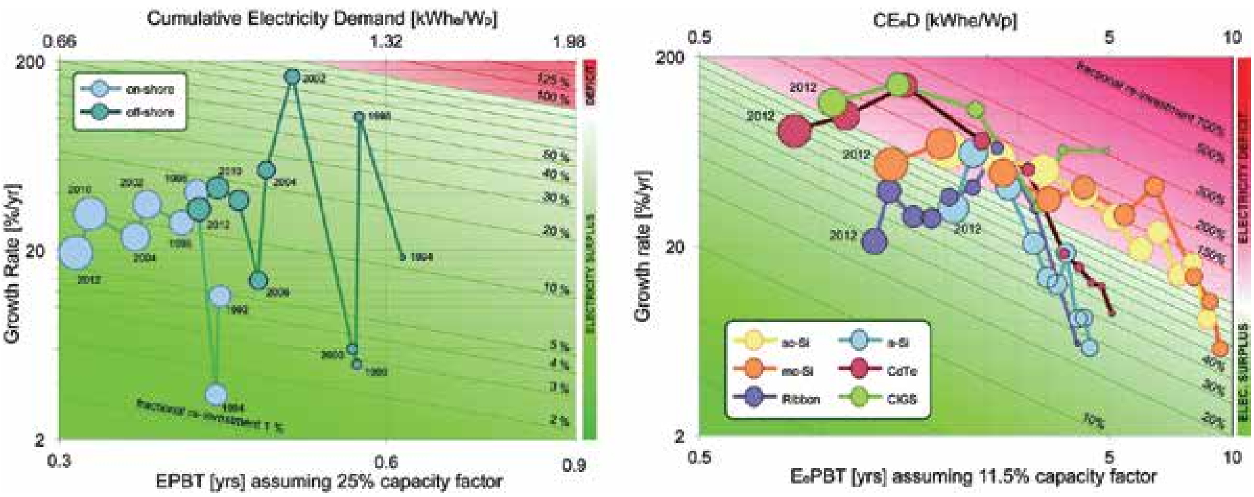

Fig. 2: Net energy trajectories for the wind (left) and PV (right) industries. The red region represents a net energy deficit and the green region a net energy surplus. Diagonal sloping lines represent the fractional re-investment, i.e. how much of the gross output from the industry is consumed by the growth of the industry.

any amount of storage pushes these technologies into electricity deficit. At the opposite end of the spectrum, ribbon silicon, mainly due to its slow growth rate, could support up to 6.84 Wh_s/W_p of battery storage (enough to provide 72 hours of back-up) without either slowing its growth rate or running an electricity deficit. In between those two cases, in order to still run an electricity surplus without slowing their growth rates, are CdTe and mc-Si, which could support 6.84 Wh_s/W_p of geologic storage, and a-Si, which could support 6.84 Wh_s/W_p of an equal mix of all storage types, but not of battery storage.

An alternate means to understand this issue is to ask the question, 'what amount of storage could be supported by each generation technology at its current growth rate without running an electricity deficit?' Or, alternatively, 'how much storage can each generation technology 'afford to buy' with its electricity surplus?' Table 1 shows the answer to this question.

We can immediately see the benefit of low energetic cost for both generation and storage technologies. On-shore wind can support 371 Wh_s/W_p (enough for 82 days of back-up) of geologic storage but only 63 Wh_s/W_p (enough for 14 days of back-up) of electrochemical storage. Similarly, ribbon silicon PV, with a growth rate comparable to that of on-shore wind, but a higher CEeD, can support 130 Wh_s/W_p (enough for 57 days of back-up) of geologic storage or 22 Wh_s/W_p (enough for 10 days of back-up) of electrochemical storage. CIGS and sc-Si cannot support any amount of storage, since they are already operating at a deficit.

HEADLINES

NEC acquires grid energy storage and commercial systems business of A123 Systems from Wanxiang

NEC Corporation has announced the acquisition of the A123 Energy Solutions business unit of A123 Systems, LLC. This acquisition, for approximately $100 million, strengthens the energy storage capability of NEC's smart energy business, a core segment of its Mid-term Management Plan's commitment to social infrastructure. A123 Energy Solutions will be integrated into the NEC Group of companies and operated globally as a key element of its business. An agreement on the terms of the deal has been finalized and a new company "NEC Energy Solutions" is slated to begin operation in June under the direction of NEC. A123's existing cell manufacturing and sales, research and development, and automotive operations will remain the core focus of A123 Systems, LLC.

With this acquisition, NEC will become the world's leading supplier of lithium-ion grid energy storage systems. A123 Energy Solutions has deployed over 110MW of its Grid Storage Solutions (GSS)™ worldwide with the vast majority of these systems already in revenue service. The company will continue to supply systems using A123 Systems' Nanophosphate® lithium-ion cells and support all existing installations. NEC Energy Solutions, with access to NEC Corporation's world-class information communications technology (ICT) and A123 Energy Solutions' system integrations expertise, is now better prepared to address the increasing global need for energy storage. In addition, NEC's high quality, cost-effective lithium-ion technology adds to the ever-growing portfolio of energy storage technologies available for future use in A123 Energy Solutions' GSS platform. At the same time, NEC will leverage A123 Energy Solutions' experience in commercial batteries in order to serve NEC's telecommunication carrier, enterprise and government customer base, thereby helping to drive the global expansion of NEC's smart energy business.

Another point worth noting is the comparative cost of generation and storage. The energetic cost of supplying 72 h of geologic storage to support wind is comparable with the energetic cost of deploying wind (both less than 1 kWh_e/W_p); however, the cost of 72 h of battery storage costs around three times as much. As such, it may be more cost effective to deploy more wind capacity to mitigate variability in the output, rather than supporting wind power with battery storage. Conversely, the energetic cost of battery storage and PV deployment are comparable, so the decision between deploying more PV or deploying battery storage is not clear cut. This issue has been examined in greater detail elsewhere.[21]

Discussion

The results clearly demonstrate the advantages of technologies (both generation and storage) with low CE_eD, as well as generation technologies with high capacity factors. Combining low CE_eD generation and storage technologies allows a greater proportion of the electrical output to be available to society, rather than being consumed by the industry to fuel its own growth. On-shore wind can support 72 hours of geologic storage while maintaining its current growth rate and still consume only around 10–20% of its own output. In fact, this combination could support growth rates of 100% per year (i.e. double in size each year) and still maintain an energy surplus.

Combining sc-Si at its current growth rate with 24 hours of battery storage would entail the technology consuming around 150% of its own electrical output in deploying new capacity. While this is clearly manageable when PV provides only a small fraction of global electricity supply, it would be difficult to sustain when PV penetration rates increase.

Conclusion

In this paper, we have presented the net energy trajectories of both the wind and PV industries. We have shown that the wind industry currently has a much lower fractional re-investment level than the PV industry, due to: lower energetic costs for system deployment (***i.e.*** $CE_eD_{wind} < CE_eD_{PV}$); wind systems achieve higher capacity factors than PV systems, so 'pay back' the energy required for their deployment sooner than PV systems (***i.e.*** $EPBT_{wind} < EPBT_{PV}$), and the growth of the wind industry is slower than the PV industry. As such, the fractional re-investment for wind is between 5 and 20% compared with between 20 and 120% for PV technol-

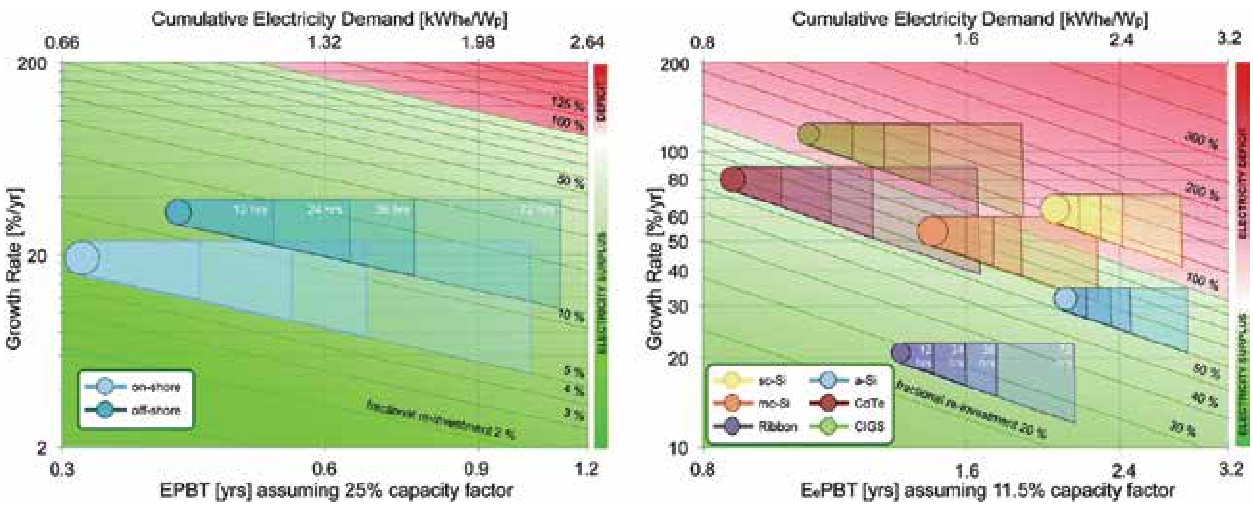

Fig. 3: Net energy diagrams for wind (left) and PV (right) technologies with the additional cost of 12, 24, 36 or 72 hours of an equal mix of all storage technologies represented as shaded regions.

					Storage		
Tech.	CE_eD [kWh_e/W_p]	EPBT [years]	Growth [% per year]	Surplus [kWh_e/W_p]	All[a] [Wh_s/W_p]	Geologic[b] [Wh_s/W_p]	Battery[c] [Wh_s/W_p]
On-shore	0.69	0.34	19	9.67	83	371	63
Off-shore	0.89	0.44	33	5.13	44	197	34
sc-Si	2.03	2.03	65	-0.48	0	0	0
mc-Si	1.46	1.46	54	0.38	3	15	3
Ribbon	1.34	1.34	21	3.38	29	130	22
a-Si	2.08	2.08	32	1.06	9	41	7
CdTe	0.85	0.85	81	0.39	3	15	3
CIGS	1.05	1.05	114	0.18	0	0	0

[a] CE_eD: 0.117 kWh_e/Wh_s. [b] CE_eD: 0.026 kWh_e/Wh_s. [c] CE_eD: 0.153 kWh_e/Wh_s.

Table 1: CE_eD, EPBT, growth rates and the amount of storage that each watt of capacity could support, disaggregated by the generation type and storage mix. Note that there are some differences between the values here and the median values for PV and wind from the meta-analysis due to the assumed energetic cost reductions that have occurred according to the learning curve model, as described in the ESI†

ogies.

We then analyzed the additional energetic requirement of deploying storage to 'back-up' wind and PV systems, which penalized generation technologies by either increasing their fractional re-investment or slowing their growth rate (or a combination of both). Wind technologies produce enough electricity surplus to support up to 72 hours of either geologic or battery storage, or an equal mix of all technologies, as does ribbon silicon PV, mainly due to its low growth rate. Since CIGS and sc-Si both run an energy deficit even before the inclusion of storage, they cannot support any level of storage. CdTe, mc-Si and a-Si can afford up to 72 hours of geologic storage, but fewer hours of either mixed technology or all-battery storage.

We must note that this analysis considers only the energetic cost of deploying storage. It does not consider the energetic, round-trip efficiency losses associated with passing energy into and out of storage, which has

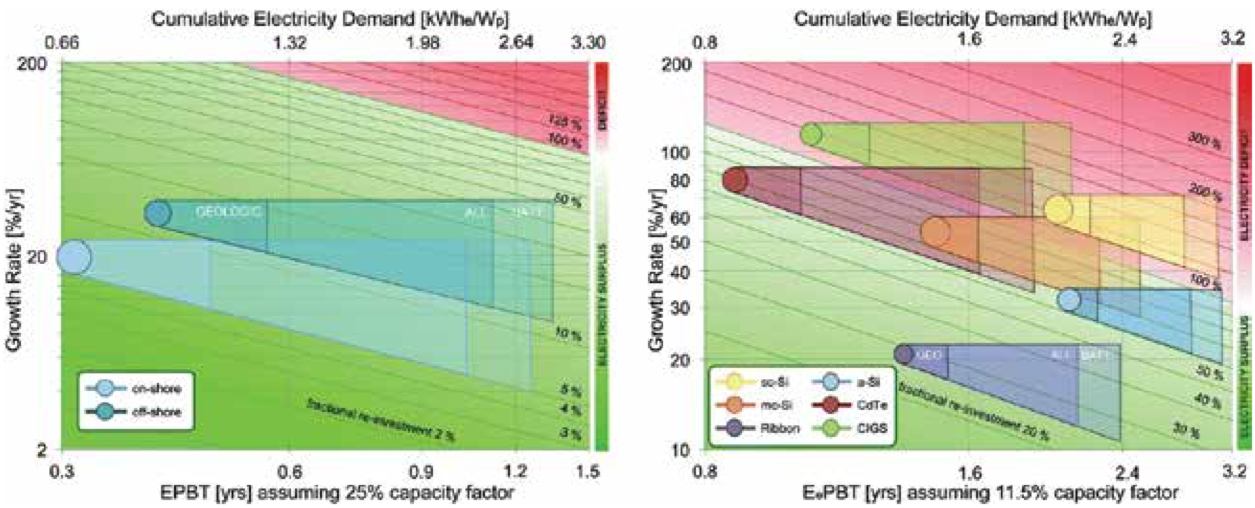

Fig. 4: Net energy diagrams for wind (left) and PV (right) technologies with the additional cost of up to 72 hours of storage represented as shaded regions, assuming either only geologic storage (GEO), all storage technologies allocated equally (ALL), or only electrochemical storage technologies (BATT).

been addressed in another study.[21] Nor does this analysis consider either operating the storage technology at lower depths of discharge—thus requiring larger amounts of storage to be built—or the replacement cost of electrochemical storage technologies, whose lifetimes are generally less than those of either wind or PV systems. For example, a PbA battery will achieve around 700 cycles at 80% depth of discharge.[18] Assuming charging and discharging once in every three days, the battery will last under six years. This means that the battery will need to be replaced at least four times to match the 25 year lifetime of either the wind or PV system. Geologic storage technologies, on the other hand, have much longer lifetimes. As such the benefits of geologic storage are actually greater than outlined in this analysis.

Financial costs are not the only drivers of societal benefits of generation and storage technologies. This analysis clearly highlights the benefits of combining low energy intensity (i.e. low CE_eD) generation and storage technologies. As such, it is important to supplement financial cost-based analyses of technologies with energetic analysis. It is also important for manufacturers of both storage and generation to continue to explore means to further reduce the CE_eD of their technology.

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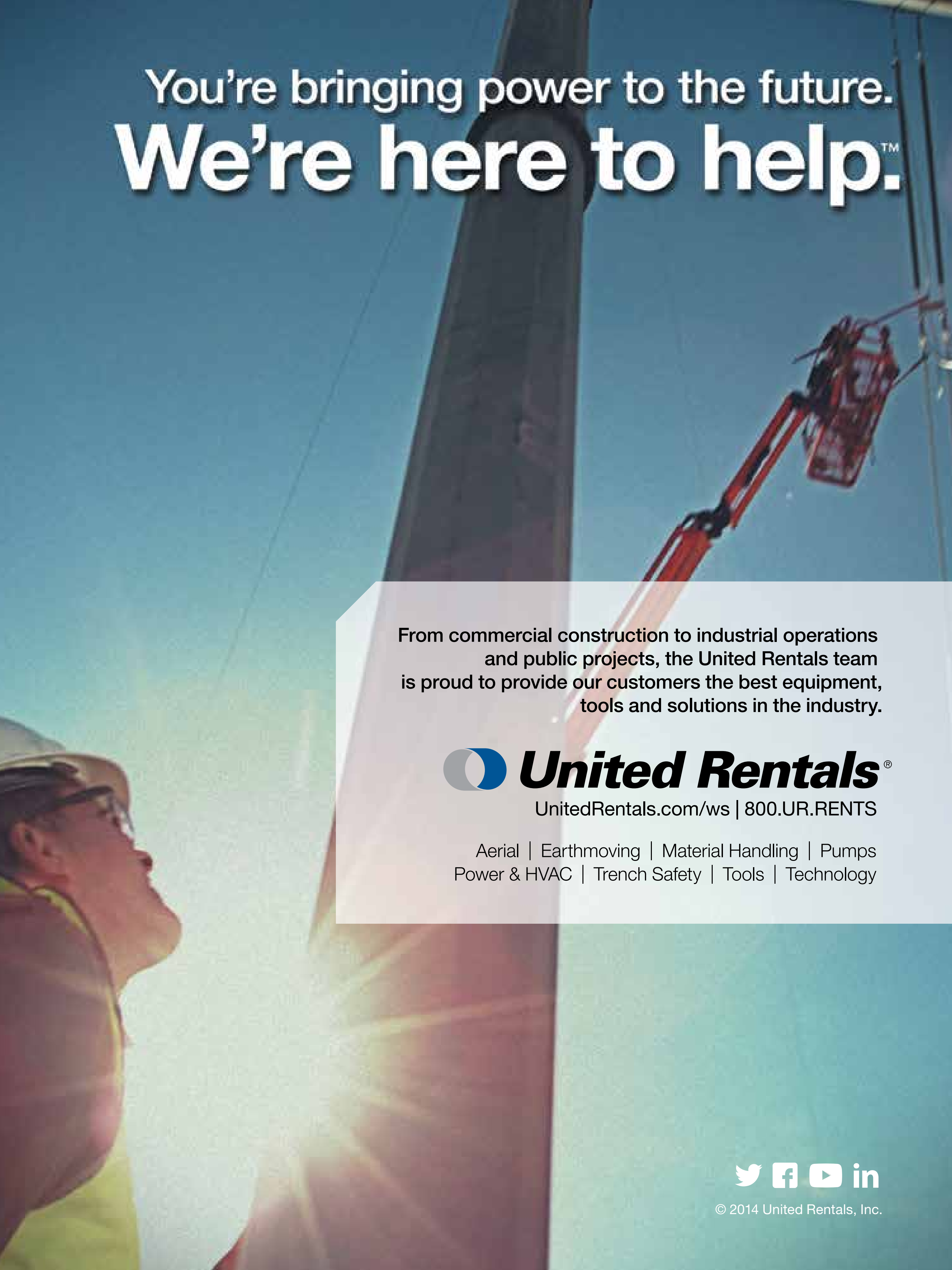
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RES Americas announces operation of first energy storage system

Renewable Energy Systems Americas Inc., a leader in the development and construction of wind and solar projects in North America, is pleased to announce the operation of the company's first energy storage system.

RES Americas conceived, developed, and constructed the energy storage system, which it will own and operate. Located in Sunbury, Ohio, just outside of Columbus, the system is comprised of a +/-4MW (8MW total range)/ 2.6MWh lithium battery that will provide a service called "frequency regulation" to PJM, the largest grid operator in North America.

The project utilizes lithium iron phosphate, an inherently safe variant of lithium battery chemistry, and consists of two containers that house batteries weighing approximately 20 tons each, as well as a third container that converts the direct current (DC) output to alternating current (AC) for the grid. The equipment was supplied by BYD America.

"Leveraging our renewable energy, transmission, and distribution construction experience, we are uniquely placed to excel in energy storage, whether as an IPP, or as an EPC for a utility owner. We are excited to be one of the leaders using this new technology, ensuring that RES continues to be innovative and create value for our customers," said Andy Oliver, senior vice president, Energy Storage and Technology, RES Americas. "We look forward to additional projects that combine affordability, safety, and best-in-class quality," Dr. Oliver continued.

The global market for energy storage is expected to grow rapidly in the coming years. Navigant Research estimates that worldwide revenue from advanced batteries for utility scale energy storage applications will grow from $164 million in 2014 to more than $2.5 billion in 2023. Frequency regulation represents a small fraction of the numerous services that energy storage can provide to the grid.

RES Americas anticipates delivering the company's second 4MW system in June 2014 in Ontario, Canada for the grid operator IESO. The company is currently marketing additional fully-developed frequency regulation projects in PJM.

INNOVATION

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PMG vs. DFIG—The Drivetrain Technology Debate

Challenging the industry on the superior total life cycle cost efficiency and reliability of PMG-FPC drivetrain solutions

From The Switch

In the wind power industry, the debate on which generator and converter option makes for the best modern wind turbine drivetrains is still raging. Numerous technology experts and industry commentators promote the use of the double-fed induction generator technology, while expressing doubts about the advantages of the permanent magnet generator (PMG) approach.

Total life cycle cost efficiency

It is sometimes claimed that permanent magnet generator (PMG) and full-power converter (FPC) drivetrains are more expensive than double-fed induction generator (DFIG) drive trains. However, research has established that when every investment and operational factor is taken into account, PMG-FPC drivetrains work out to be a cheaper, more cost-effective option over the total life cycle of the turbine.

True costs seen in grid connection

The lower grid connection costs of PMG-FPC equipped turbines represent a significant advantage over DFIG models. Efficiency and grid compliance are the top demands when it comes to generator selection. These factors, along with high annual energy production (AEP) and reliability, are very important from an investment point of view. While partial converters may have improved somewhat in grid code compliance, full-power converters remain the preferable option. As stated in the report, "Power System Architecture: Finding the Best Solution for a 5MW Turbine," published by the engineering consulting company NextWind: "PMG is also a good choice for grid code compliance. Due to the full converter, all requirements for harmonics, power factor control, and grid fault ride-through can be met easily."

DFIG technology now complies with the grid codes by adding hardware and software at the expense of extra costs. This is a simplistic answer to the problem, and is more of a quick fix than a concrete solution. With regards to DFIG, the NextWind study explains: "There is extra cost related to meeting new grid codes with the DFIG. With fault ride-through and power factor capability, the DFIG converter becomes similar in size and cost to the full converter."

A key benefit of PMG-FPC drivetrain technology is the fact that it already includes features such as reactive power generation and low voltage ride-through (LVRT). These inherent benefits level the playing field when making comparisons with the cheaper upfront costs of double-fed induction generator drivetrains, which also need additional VAR support to make a connection to the network.

The long-term advantage comes from the extra energy produced with the higher power curve efficiencies of PMG technology. The PMG's maximized energy production is what gives significantly higher income and profitability. Research conducted by Peter Jamieson and presented in the report, "Innovation in Wind Turbine Design 2011," showed that PMG-FPC drivetrains produce more energy in low or medium wind conditions, leading to better income.

PMG-FPC drivetrains actually improve efficiency over the full operational range of the turbines. Although some claim that DFIGs are more efficient than PMGs at full load generation and in high, steady winds, in reality, the efficiency of the PMG-FPC and the DFIG plus partial converter are similar when operating at 100 percent power. However, we know that this situation rarely occurs, and in general working conditions, PMG drivetrains have proven to be more efficient. In fact, the lower the power, the lower the efficiency of the DFIG. In addition, the Ohmic losses in the DFIG winding due to the excitation power, which are more or less constant regardless of the output, also reduce the DFIG's efficiency.

According to NextWind, "PMG has the highest annual power output, with a 2.2% increase in AEP over DFIG for an IEC (International Electrotechnical Commission) class II site." PMG has a much higher efficiency curve, and this is especially true when operating at partial power, where the highest number of operational hours is spent. The report goes on to state: "A significant difference in power output becomes apparent when the operating speed range is taken into account. The PMG can begin producing power at very low rpms, but the DFIG is limited to a synchronous speed of less than 30%."

In terms of operational performance, using the nominal point as the benchmark leads to incorrect assumptions, as the majority of a wind turbine's lifetime is spent generating power at partial wind speeds. In effect, the lower the nominal speed of the DFIG, the poorer its operating characteristics, mainly regarding efficiency and power factor. Due to this, DFIGs are not used in direct-drive or medium-speed turbines at all. So, the only choice for those turbines is a synchronous machine, and most often, due to poor electrical performance, DFIG cannot be used on direct-drive machines at all.

Generator losses are always lower with PMG than with DFIG, since there are no excitation losses. The fact that DFIG only needs a partial converter reduces the difference in total drivetrain efficiency between these two concepts—especially at nominal loads. At partial loads, however, there is a significant difference—and this is where a wind turbine operates most often with fluctuating wind speeds. That's why a PMG drive train results in higher AEP.

Another perceived advantage of turbines equipped with DFIG is that they only require partial converters, because only 25–30 percent of the input power is fed to the grid through the converter from the rotor; the rest goes directly to the grid from the stator. Because of this, little power is lost via the converter. Indeed, this idea is based on the incomplete assumption that the full-power converters required by PMGs are more expensive than the 20–35 percent rated capacity partial converters required by DFIG drivetrains. But the true question is: Which is more cost effective? Even in this case, PMG-FPC turbines work more efficiently because of the additional energy yield they provide in the partial power range over the entire lifetime of a wind turbine, which ensures a better return on investment.

At medium or low wind speeds, PMG models are undoubtedly more efficient, but what about at high wind speeds? When it comes to high-speed drivetrains, the outdated belief that PMG does not appear to offer any great advantage over a modern DFIG when used with a high-speed drivetrain needs clarification. The situation varies wildly depending on the wind class. With high average-wind speeds, the DFIG turbine operates closer to the rated point, and can close the efficiency gap on PMGs to some extent. However, even during high average-wind speed, PMG still offers advantages over a DFIG in terms of installation, operation, maintenance, and actualized value for money. Maximized AEP is one of the real priorities for customers and investors, and PMG turbines can accrue up to 7 percent more than DFIG designs, even when used with a high-speed drivetrain.

PMG designs also enhance reliability and serviceability, leading to lower O&M costs. It is important to bear in mind the required servicing and total reliability of the drive train. As the wind energy update by Sciemus, entitled "Big Data—How Applied Analytics Can Enhance Your O&M Programmes," confirms, PMG designs have a "comparatively low number of electrical faults and failures (0.59 failures per year vs. 0.69 for other technologies)." The report continues: "The latest PMG machines are most reliable in terms of downtime per unit at 1.98 days per year, where all other technologies are >2.36 failures per year—an 18% improvement. This is due to low failure rates across each of the seven failure modes and indicates that industry learning and feedback is being incorporated into the latest machines."

One Chinese wind turbine manufacturer realized enormous cost savings by minimizing its O&M crew.

Compared to PMG technology, turbines operating with DFIG technology required a 2.8 times larger workforce for a comparable number of installed turbines.

In its recent study, NextWind estimated that annual service costs for DFIGs, including the additional service costs of the needed gearbox, would be 20–30 percent higher than the service costs for PMGs. The report goes on to say: “The improvements in annual energy production (AEP) and cost of service for the PMG outweighs the higher up-front costs, and that a wind turbine with a PMG will achieve a lower cost of energy compared to a wind turbine equipped with a DFIG.”

The rare-earth magnets required by PMGs can be perceived as an inherent risk, on the grounds of cost, price volatility, and availability. While it is true that rare earth is needed for PMG turbines, magnets are not as expensive as they once were, and the price level has stabilized considerably. The amount of rare earth magnets needed varies depending on the generator type: direct drive, medium speed, or high speed. Also the magnet arrangements can be optimized to lower the amount of rare earth materials needed. Finally, this price premium difference is offset by the lack of winding needed in the rotor, as needed with DFIG; manufacturing and assembling the rotor winding is time-consuming and expensive.

NextWind’s study came to the conclusion that PMGs are “the clear choice for optimizing all factors affecting the cost of energy of the installed turbine.”

The Reliability Factor

It’s wrongly assumed that PMG-FPC solutions require lots of potentially unreliable electronics. This commonly admitted myth states that full-power converters are not very reliable because they rely greatly on power electronics, which would be more prone to faults than gearboxes. This is inaccurate. In reality, the amount of electronics used in PMG-FPC drive trains is comparable to DFIG systems. Indeed, partial-load converters rely on the same electronics as full-power converters, but only scaled to lower power ratings. Power electronics failures will have the same consequences on PMG-FPC and DFIG plus partial-converter drivetrains alike.

More importantly, it is worth noting that there are no electronics used in the PMG generator itself, only in the converters. Furthermore, when considering a multi-megawatt system, a DFIG solution most likely consists of only one converter for the rotor connection, while a full-power converter system can consist of several parallel power threads. As semiconductors do fail, it is better to have the still healthy power threads in operation despite a failure in one of them, allowing the turbine to run at limited partial power, rather than having the whole turbine at a standstill due to a failure in power electronics.

The NextWind report came to the conclusion that PMGs have higher reliability and lower maintenance costs than DFIGs due to better heat performance, as well as being able to function without slip rings or encoders. “The DFIG creates a negative impact on reliability and increased maintenance cost due to increased gearbox loads from grid transients. Shifts in grid voltage and frequency result in high-cycle tooth-loads on the gearbox, resulting in micro pitting. Additionally, slip rings require inspection at six-month intervals and frequent replacement. In low temperature or marine environments, the maintenance interval may be even shorter.”

Sciemus engineering experts proved that “Direct Drive and hybrid PMG machines are some of the most reliable on the market.” This was “in part down to the superior reliability of the PMGs (0.11 failures per year) in comparison to the other generator technologies shown (0.12 – 0.14 failures per year).”

PMGs require the use of NdFeB magnets, which are sensitive to corrosion and heat. For this reason, some industry commentators claim that electrical losses could climb rapidly due to excessive heat. They also wrongly assume that there is a risk of reversed polarity or permanently losing magnetic field strength.

Such statements seem to ignore the fact that NdFeB magnets are always coated, which helps to protect them from corrosion very efficiently. Hermetic sealing is also applied when assembling the rotor, which also helps in this regard. It is also untrue that there is a sudden jump in electrical losses if the temperature rises above 80° C. In addition, the risk of reversed polarity is always taken into account during the design phase as well as tested with the prototype generators in the test bench. With these precautions in place, the risk of reversed polarity is close to zero.

From a manufacturing perspective, having the appropriate production quality standards and engineering skills is necessary to ensure the performance of the PMG-FPC drive trains. Manufacturing large PMGs for direct-drive turbines requires a high degree of expertise. Indeed, air gaps between rotor and stator demand tighter tolerances, and being able to maintain these standards when machining components 6 meters in diameter demands a level of skill and expe-

rience not found in all manufacturers. But with proper design and manufacturing standards in place, there are no special arrangements needed to maintain an air gap in large, direct-drive turbines.

PMG-FPC solutions offer much better maintenance conditions than DFIG drivetrains. PMG designs enhance reliability and serviceability as they require no slip rings or brushes and comply more easily with grid codes. Although DFIG solutions have made some improvements to historical challenges like brushes, bearings, and insulation, as long as DFIGs still use brushes, then they are likely to encounter problems such as sparks, consumable parts, and the need for regular maintenance and replacement. Brushes must be replaced regularly, whereas the so-called brushless DFIG machines have significant drawbacks, such as low efficiency, larger sizes and a very complex physical construction. Therefore, they are not widely used in wind applications.

As Sciemus also confirms, PMG designs have a "comparatively low number of electrical faults and failures." The report continues on to say that, in terms of downtime, the latest PMG machines are most dependable, thanks to the minimal rate of failure in each of the seven modes.

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AN OVERVIEW OF PMG AND DFIG DRIVE TRAINS		
PERFORMANCE	MACHINE TYPE	
	DFIG asynchronous wind power generator	Permanent magnet wind power generator
STATOR	Same	Same
ROTOR	Rotor coil	Permanent magnet
BEARING	Same	Same
SLIP RING AND CARBON BRUSH	Available	Not needed
MANUFACTURING	Complicated process to manufacture rotor	Simple process to manufacture rotor
MAINTENANCE	Heavy maintenance work and high cost for rotor slip rings	No need for rotor maintenance
CONVERTER	25-30% output power	Full power
ABILITY OF LVRT	Available	Available
REACTIVE POWER AND ADJUSTMENT ABILITY	Varies according to the generator speed	100% across the entire speed range
ABILITY TO CONNECT AND SUPPORT POWER GRID	Poor	Very good
ADVANTAGES	The initial investment is lower	1. Magnet is used for rotor; no coils, coil connection or slip ring needed 2. No need for rotor maintenance 3. Applicable to high-, medium- and low-speed generator 4. High efficiency 5. Generator is lighter and size is smaller 6. Smaller cogging force 7. Higher annual power output
DISADVANTAGES	1. Difficult to service rotor, especially if problems happen in the rotor coil and rotor wire connection during turbine operation 2. Not applicable to medium-speed and low-speed generator 3. Low efficiency 4. Larger and unstable cogging force 5. Larger bearing current	1. The initial investment is higher 2. Requires professional design software for complicated calculation 3. Requires more sophisticated process

CONSTRUCTION

BOP/EPC • Project Status• Siting • Equipment • Project Due Diligence • Services

AWEA report: Record wind farm projects under construction

Wind industry builds recover after slow start due to late PTC extension

Wind energy continued its forward march in 2013 as an ever-growing piece of the mainstream U.S. electricity mix, with a record number of projects and generating capacity under construction by year's end, billions of dollars of continued private investment, and new records for generation in many areas, according to the AWEA U.S. Wind Industry Annual Market Report Year Ending 2013, released on April 10.

The U.S. industry ended 2013 with 61,110 MW operating in the U.S. across 46,100 wind turbines in 39 states and Puerto Rico. The 905 utility-scale wind projects operating here exceeded 4 percent of the U.S. electricity generation during 2013, and are now able to power the equivalent of 15.5 million American homes. They will continue to deliver new, affordable, clean generation year after year. Meanwhile, an average of $15 billion a year is invested in new projects, resulting in the industry posting 19.5 percent average annual growth over the past five years.

"Increasingly, America is powered by wind energy," said AWEA CEO Tom Kiernan. "As utilities and Americans become more familiar with this affordable and reliable energy source, they want more of it. Our industry is responding with record construction numbers, more business for American factories, and more deployment of wind energy that has become a new cash crop for our farmers and ranchers."

The year began slowly after a last-minute extension of the federal Production Tax Credit (PTC) for renewable energy on Jan. 2, 2013. The supply chain had slowed down during the months preceding the threatened expiration. As a result of the slowdown and the months needed to region momentum, the industry saw a 92 percent drop in installations, down from a record 13,131 MW in 2012 to just 1,087 MW in 2013. With a historic 12,000 MW and 100 projects under construction as 2013 drew to a close, this boom-bust pattern could continue if policy uncertainty continues.

Wind energy has become the primary choice for new energy capacity in wind-rich regions. Between 2011 and 2013, wind energy delivered roughly 60 percent or more in the Pacific Northwest, Plains states, and Midwest, and as much as 80 percent in the upper Midwest. As a matter of fact, renewable energy sources were the single largest source of new energy capacity in all regions across the country outside of the Southeast and Mid-Atlantic, from 2011 through 2013.

Wind's continued market penetration is also evident nationally: It contributed 31 percent of all new electric generation capacity in the U.S. over the past five years, underscoring how both utilities and ratepayers are gaining a better understanding of wind's affordability, reliability, and other benefits.

Generation & penetration records

Wind energy provided over 60 percent of the electricity on utility Xcel Energy's Colorado system at one point last year, among several regions that broke records for wind generation at a given time.

Year-round, wind energy in 2013 topped the 25 percent milestone in both Iowa and South Dakota. In total, wind energy comprised 4.13 percent of the nation's electricity generation mix by year's end.

Advancing technology lowers costs

The cost of wind energy dropped 43 percent between 2008 and 2012, according to the U.S. Department of Energy. That reduction comes largely from the industry's continuing technological advances in several areas, from improved siting techniques to larger rotor diameters and taller towers, which now average 97 meters and 80.3 meters respectively, increasing energy production by accessing higher wind speeds at taller elevations.

Geographically disperse benefits

Wind energy activity is now occurring in all 50 states, from project construction and operations to wind-related manufacturing. The 905 U.S. wind projects span 39 states while the 560 manufacturing facilities span 43 states. The majority of U.S. Congressional Districts, over 70 percent, have a wind project, a manufacturing facility or, both.

Positive environmental impact

The report notes that operational wind energy projects, combined with the projects under construction, will avoid 115 million tons of carbon dioxide emissions annually—more than 5 percent of U.S. power sector emissions—while avoiding the consumption of over 36 billion gallons of water each year, because wind turbines use virtually no water in operation.

Transmission infrastructure build-out

One important trend that bodes well for the industry is in the area of transmission, which is needed to link America's world-class wind resources with demand centers. Over 10,000 MW of new transmission capacity was completed in 2013, and near-term projects could deliver another 60,000 MW of wind energy—allowing a doubling of the total amount of capacity installed today. These power lines result from years of work, which must continue if growth is to be sustained.

The robust construction pace and other favorable indicators come as discussions continue in Congress over extension of the PTC, which expired at the end of 2013. The wind industry needs an extension of tax incentive in 2014 to restart the development process and continue the exciting momentum that ended 2013

HEADLINES

ICUEE—The Demo Expo takes number two spot in top-trade-shows list

ICUEE—The Demo Expo was recently named the number two spot in the recently-announced Top U.S. Trade Shows list from the Trade Show News Network (TSNN).

TSNN annually ranks shows by exhibit space net square footage. For 2013, ICUEE won for its record-breaking size of more than 1.17 million net square feet, second only to the 2013 CES show. TSNN is a leading online information resource for the exhibitions and events industry.

The next ICUEE, International Construction and Utility Equipment Exposition, will be held September 29-October 1, 2015 at the Kentucky Exposition Center in Louisville, Kentucky.

The biennial show features extensive test-drive opportunities where attendees can operate the equipment themselves in job-like conditions.

"Attendees say this is where they prepare for the future and exhibitors cite the high quality of attendees," stated Sara Truesdale Mooney, ICUEE show director and AEM senior director, exhibitions and strategy.

"We're planning for more equipment demos and interactive product demonstrations than ever before and targeted industry best-practices education. ICUEE 2015 will provide the products and knowledge attendees need to stay competitive."

ICUEE perennially ranks among the top five in trade-show-industry exhibition rankings. AEM, the Association of Equipment Manufacturers, is show owner and producer and focuses on creating a high-quality show experience. AEM shows are industry-run in which participants have a voice in show planning, industry partnerships enhance value, costs are carefully monitored, and revenues go back into industry services.

ICUEE targets utilities and utility contractors in the following sectors: electric, telecommunications, wastewater, water, natural gas, cable, and rail. For more information on attending or exhibiting, visit www.icuee.com .

MANUFACTURING

Production • Fabrication • Components • Supply Chain • Materials • Tooling • Machinery

ABB installs record-breaking EFD Induction system for short-circuit ring brazing

Power generation and distribution giant ABB recently installed the largest single-shot shortcircuit ring brazing system yet developed by EFD Induction. The system, which was installed at the ABB plant in Vittuone outside Milan, Italy, can braze rings with a diameter up to 1,500 mm.

"This system is a milestone," says Alessandro Mariani of EFD Induction Italy. "Our previous record for a one-shot short-circuit ring brazing system was 1,200 mm, so the system developed for ABB represents quite an increase. And of course, to be selected by such a demanding customer as ABB is always encouraging."

The system comprises customized coils, an EFD Induction Sinac 250/320 power source, and a mounting table. The system's first project was to braze a 1,500 mm diameter shortcircuit ring for a wind tunnel motor. "The end user," says Mariani, "is one of the world's most famous sports car manufacturers, which further testifies to our ability to meet the most stringent quality demands."

According to Stefano Chieregato of ABB, he and his colleagues examined proposals from six companies before opting for the EFD Induction solution. "There were several reasons behind our choice of EFD Induction for this critical piece of equipment. First, their proposal made technical and economic sense. Second, the company has deep expertise in the field. And third, ABB in Italy has had positive experiences with EFD Induction heating solutions for other applications."

EFD Induction is one of the world's leading suppliers of induction-based short-circuit ring brazing systems. "That's right," says Mariani. "We have even devised a specialized induction coil that equalizes the temperature around the ring. This coil minimizes energy input into laminations, thereby protecting the shaft from heat and preserving the ring's integrity."

HEADLINES

TPI Buys out JV Interest in Turkey

TPI Composites has announced that it has acquired the remaining twenty-five percent interest in its joint venture wind blade operation in Izmir, Turkey.

TPI launched the business in 2012 with a local partner ALKE ÎN™AAT and has grown the operation into the largest wind blade manufacturer in the region.

TPI has invested more than $35M to fully capitalize the Turkey operation, including a complete upgrade to its 355,000 square-foot building.

"We are very pleased to have signed long-term agreements for our initial capacity in Turkey with leading customers in the region," said Steve Lockard, president & CEO of TPI Composites. "It is a great thrill to see our world-class operation take shape and ramp to its full capacity."

Williams Form Engineering and MMFX align for high-strength, corrosion-resistant products

Northstar Endeavors, LLC and Alphatec Nordeste Complete License Rights Agreement to Manufacture Towers

Northstar Endeavors, LLC, dba Northstar Wind and Alphatec Nordeste, announced the completion of a Patent & Know-How License Rights Agreement, whereas Northstar grants Alphatec the exclusive license to Northstar's intellectual property, within the territory of Brazil, to design, manufacture, construct, and sell towers using the IP.

Northstar has developed a line of modular tower solutions for MW wind turbines using its patent and patent pending technology.

The Northstar Modular Tower (NMT) design provides the wind industry a cost-effective solution to build taller towers for larger turbines.

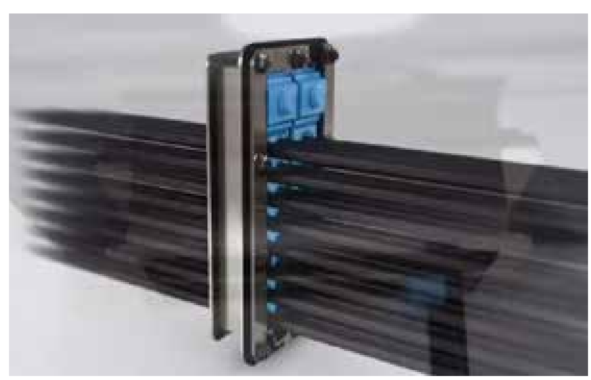
As stated by Jeff Willis, president of Northstar, "This agreement launches our global initiative of licensing our technology for our modular tower solution. We could not be more excited about teaming up with Alphatec and their team to help them to become a major tower supplier in the Brazilian market." He goes on to say, "This agreement opens up further opportunities for turbine manufacturers and developers to take advantage of the NMT benefits."

Alphatec will be expanding on its energy related businesses by developing its WT™series wind towers utilizing the Northstar patented technology for 80-140m towers. Alphatec is building a dedicated manufacturing facility for the towers and tower components that is scheduled to come online in 2016.

PRODUCT

Free web tool facilitates cable transit design and installation

Roxtec recently announced the release of its Roxtec Transit Designer 2.0—a free, web-based tool that simplifies both product selection according to needs and requirements and the process of designing, purchasing, and installing cable and pipe transits.

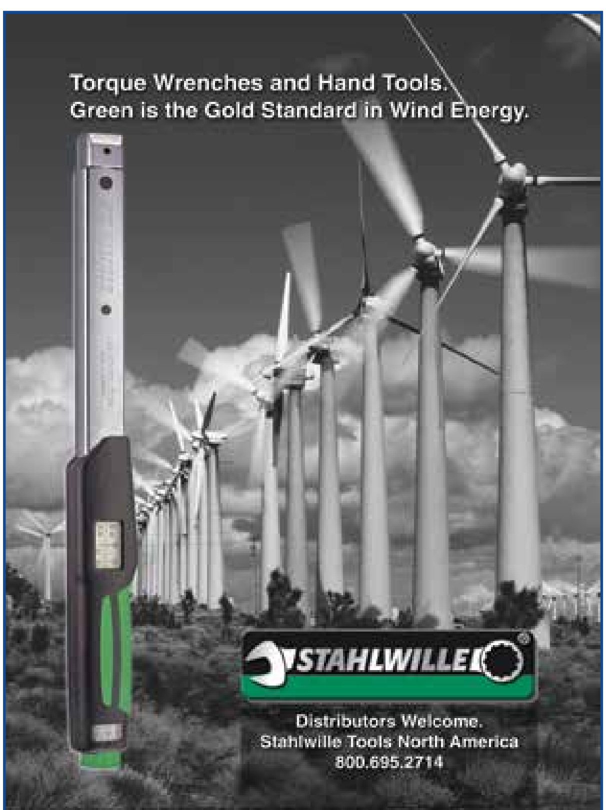


Giuseppe Principato is an instrument designer in Italy and one of thousands of designers and engineers in more than 80 countries who have already discovered the benefits of the new design software. He works with tasks such as developing material requisitions for bulk materials as well as with preparing cable routing, cable entries, wiring, installation details, and job specifications.

"I use the Roxtec Transit Designer every time a multi-cable transit is accepted or requested by our customer," he said. "It is easy to use and understand, and it helps me save time. You can customize cable transits and easily change the arrangement of the transit whenever you need."

Simple enough that designers just enter cable schedule, sealing requirements, and installation preferences—the tool generates documents such as bill of materials and CAD drawings. They can share their work with project teams anywhere in the world. And the chat function offers them instant access to the Roxtec expertise.

To start using the Roxtec Transit Designer, designers and engineers are invited to register at https://transitdesigner.roxtec.com/us/start .



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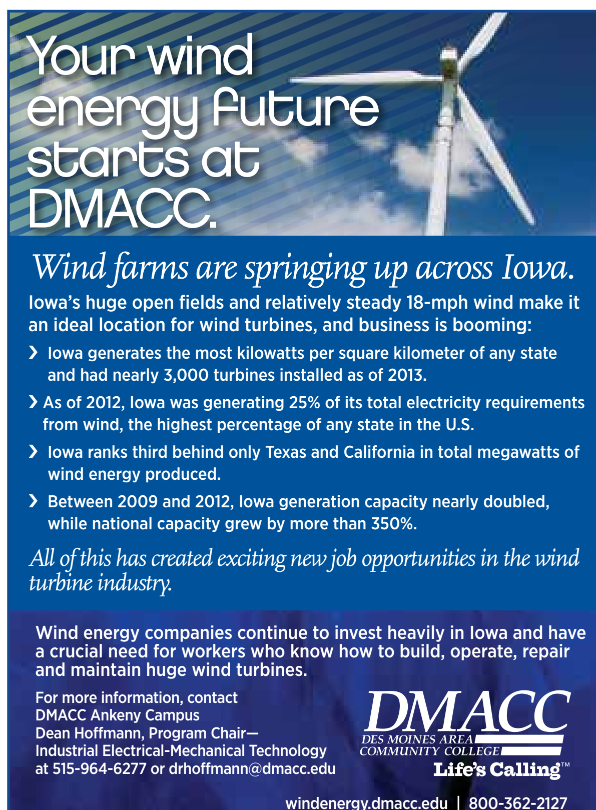

Your wind energy future starts at DMACC.
Wind farms are springing up across Iowa.
Iowa's huge open fields and relatively steady 18-mph wind make it an ideal location for wind turbines, and business is booming:
Iowa generates the most kilowatts per square kilometer of any state and had nearly 3,000 turbines installed as of 2013.
As of 2012, Iowa was generating 25% of its total electricity requirements from wind, the highest percentage of any state in the U.S.
Iowa ranks third behind only Texas and California in total megawatts of wind energy produced.
Between 2009 and 2012, Iowa generation capacity nearly doubled, while national capacity grew by more than 350%.
All of this has created exciting new job opportunities in the wind turbine industry.
Wind energy companies continue to invest heavily in Iowa and have a crucial need for workers who know how to build, operate, repair and maintain huge wind turbines.
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Going for the record

Altaeros Energies to attempt wind power generation at 1,000 feet with Alaska High Altitude Wind Turbine

Altaeros Energies, a wind energy company formed out of MIT, announced that its Alaska demonstration project is set to break the world record for the highest wind turbine ever deployed. The $1.3 million, eighteen-month project will deploy the Altaeros BAT at a height 1,000 feet above ground.

At a height of 1,000 feet, the BAT (Buoyant Airborne Turbine) commercial-scale pilot project in Alaska will be over 275 feet taller than the current record holder for the highest wind turbine, the Vestas V164-8.0-MW. Vestas recently installed its first prototype at the Danish National Test Center for Large Wind Turbines in Østerild, with a hub height of 460 feet and blade tips that stretch over 720 feet high.

The BAT uses a helium-filled, inflatable shell to lift to high altitudes where winds are stronger and more consistent than those reached by traditional tower-mounted turbines. High strength tethers hold the BAT steady and send electricity down to the ground. The lifting technology is adapted from aerostats, industrial cousins of blimps, which have lifted heavy communications equipment into the air for decades. Aerostats are rated to survive hurricane-level winds and have safety features that ensure a slow descent to the ground. In 2013, Altaeros successfully tested a BAT prototype in 45 mph winds and at a height of 500 feet at its test site in Maine.

Altaeros has designed the BAT to generate consistent, low cost energy for the $17 billion remote power and microgrid market, which is currently served by expensive diesel generators. Target customers include remote and island communities; oil & gas, mining, agriculture, and telecommunication firms; disaster relief organizations; and military bases.

"We are pleased to work with the Alaska Energy Authority and TDX Power to deploy our flexible, low cost power solution for remote communities," stated Ben Glass, Altaeros chief executive officer. "The project will generate enough energy to power over a dozen homes. The BAT can be transported and setup without the need for large cranes, towers, or underground foundations that have hampered past wind projects."

The BAT (Buoyant Airborne Turbine) project, partially financed by the Alaska Energy Authority's Emerging Energy Technology Fund, will be the first long-term demonstration of an airborne wind turbine. The project is currently being permitted for a site south of Fairbanks.

For more information, or to view a demonstration video, visit www.altaerosenergies.com.


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