

The Effect of Pitch System Reliability on Wind Power Generation’s Levelized Cost of Energy

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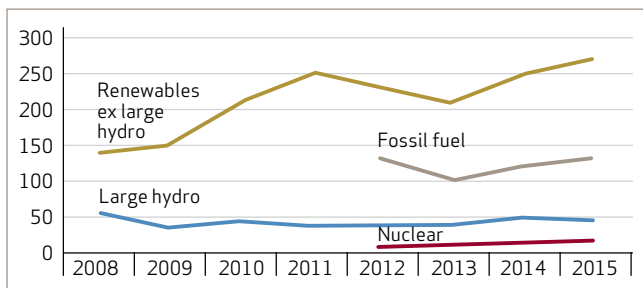
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Key Messages

- Reducing Wind LCoE is important for the industry
- Improving turbine reliability can help reduce LCoE
- Pitch systems (electric and hydraulic) currently used by the industry are major failure components
- Significant opportunities exist to improve electric pitch system reliability through design optimization
- DNV GL LCoE model shows that Moog Pitch System 3 can save up to \$1.70/MWh for a typical 3.0MW turbine

1 Renewables Dominate New Capacity Addition

Over the past decade, the substantial increase in installed capacity from clean renewables has drastically transformed the global energy landscape. Non-hydro renewables such as wind, solar, and biomass have become increasingly competitive, producing as much electricity worldwide as gas and more than twice that of nuclear.

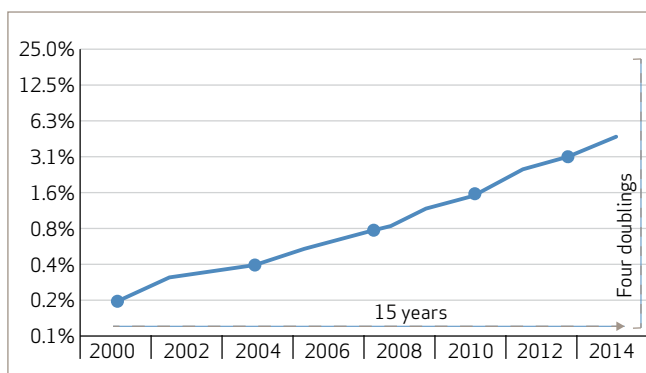


Source: Bloomberg New Energy Finance

Figure 1. Investment in Power Capacity, 2008 – 2015 (\$BN)

Much of this can be attributed to the fact that governments across the world have become more focused on reducing carbon emissions, which has allowed renewable technologies to compete with fossil fuels and other traditional power sources. In some countries, support at the state and provincial level has been a major driver of renewable energy growth as well.

In 2015, global wind installations grew by 16%, raising the cumulative installed capacity to 433GW. It took the world roughly four decades to reach the 433GW total; however, nearly 15% of it has been installed in the past year alone (63.5GW).¹



Source: Bloomberg New Energy Finance

Figure 2. Wind Share of Generation, 2000 – 2015 (% of System Total)

Wind and solar have made up the majority of global renewable capacity additions over the past decade. While government support has been a major driver of these additions, the expiration of subsidy programs and changing policy frameworks are presenting a number of challenges for renewable providers. The recent economic slowdown in China and uncertainty regarding where national policies will be headed after the 2016 U.S. presidential election have also hindered renewable projects.

These challenges, coupled with the fact that other renewables like solar photovoltaic are becoming more economical, have created an environment in which wind has to be more competitive if it is to survive and grow. As a result, the development of new and more advanced technologies that can improve turbine efficiency, reduce lifecycle costs, and lower levelized cost of energy (LCoE) will be critical to ensuring the long-term success of wind projects throughout the future.

	Capex (\$m/MW)	Capacity factor (%)	Fixed O&M (\$/MW year)	Debt ratio (%)	Cost of equity (%)	LCoE, (\$/MWh)
Country	Lowest	Lowest	Ave	Ave	Ave	Ave
Canada	1.98	33%	28,000	70%	9%	60.0
United States	1.56	29%	26,000	70%	9%	65.4
Brazil	1.29	44%	30,000	60%	15%	66.7
Germany	1.90	22%	25,630	70%	5%	78.9
UK	1.77	24%	24,090	66%	8%	85.1
China	1.28	22%	15,438	80%	10%	76.2
India	0.99	20%	16,054	70%	14%	76.8

Source: Bloomberg New Energy Finance

Table 1. Key Wind Cost Inputs in LCoE Scenarios, H1 2016

2 Turbine Reliability is a Key Factor that Contributes to Levelized Cost of Energy

LCoE is a value that measures the net cost to install and operate a turbine against expected energy output over the course of the turbine’s lifetime (incentives excluded). LCoE is a commonly used indicator of a wind energy project’s return on investment and is often the standard methodology used by governments, utilities, IPPs, and major consultants to determine the competitiveness of a specific generating facility and/or asset.

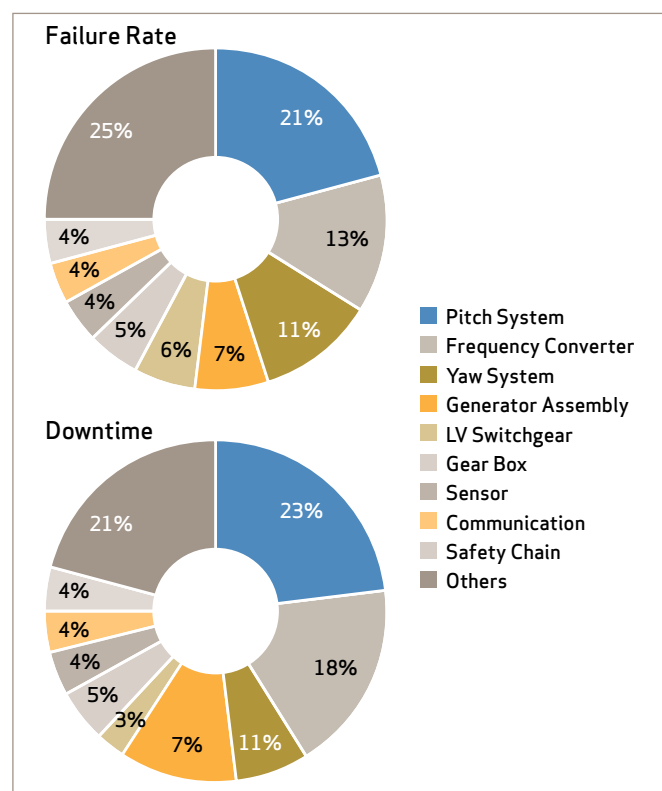
Over the past decade, average LCoE for wind generation projects across the globe has dropped to new lows. This decrease is attributable to a number of turbine-related advancements that have allowed for greater energy capture gains and increased capacity factors, including improvements in automation and electronics, longer blades, and taller towers.

There are a number of factors that contribute to LCoE, one of the most important of which is the cost to operate and maintain (O&M) the turbine. O&M costs can be defined as any costs that arise as a result of planned and unplanned activities to keep wind turbine farms operational. This includes the cost of annual service contracts and scheduled repairs, along with the cost of any equipment and/or parts whose replacement is expected throughout the lifecycle of the turbine. O&M costs associated with offshore turbines are often higher due to the difficulty involved in conducting maintenance on infrastructure. The harsh marine environment also contributes to higher failure rates for many turbine components as well.

O&M is heavily impacted by the reliability of the turbine and its components. Overall, it accounts for approximately 18 - 23% of lifetime costs in offshore turbines, and 12% in onshore turbines.²

3 Wind Industry Pain Points - Pitch System is a Major Failure Component

The reliability of a wind turbine is a product of the reliability of its components (see Figure 3). One of the challenges faced by the industry lies in understanding where efforts to improve component reliability will translate into the greatest return on investment. Most of the research done in the past on this subject has focused on mechanical and electrical system level analysis - providing very little depth in terms of failure analysis at the component level.



Source: Measuring Wind Turbine Reliability – Results of the Reliawind Project

Figure 3. Wind Turbine Failure and Downtime by Component

According to a 2011 ReliaWind research report titled “Reliability-focused research on optimizing Wind Energy system design, operation and maintenance: Tools, proof of concepts, guidelines & methodologies for a new generation”, pitch system failures account for 23% of all downtime in wind turbines – more than any other component or system. Frequency converters were the second biggest contributor, accounting for 18% of downtime, with generator assemblies and yaw systems accounting for 11% and 7%, respectively. Pitch systems also accounted for the highest percentage of all failures in wind turbines at over 21%.

Pitch systems are mounted inside the rotating hub of turbines and act as a key safety mechanism, protecting the turbines against adverse wind conditions. They are often exposed to extreme ambient conditions, including high temperature, humidity, and vibration. Hydraulic fluid leaks, fluid contamination, and fluid rotary joints are major sources of failure in hydraulic pitch systems, while motors, drive electronics, and power back-up batteries are prone to frequent failures in electric systems.

Typically, pitch systems account for less than 3% of a wind farm’s CapEx, and because of this, they often attract very little attention during preliminary design phases. In the past, OEMs have largely focused on the optimization of bigger ticket items such as gearboxes and rotor blades; however, given the percentage of downtime that is a direct result of pitch system failures, improving pitch system performance and reliability has become increasingly crucial.

4 Benchmarking Pitch System Reliability

This year, Moog partnered with DNV GL in a reliability benchmarking and LCoE analysis project with the following objectives:

1. More accurately quantify the impact of pitch system reliability on turbine failure rate.
2. Quantify the improvement in LCoE due to improvements in pitch system reliability achievable through design optimization.

Making use of internal datasets and operational data provided by Moog, DNV GL created a benchmark of pitch system reliability based on field data from a total of 69 projects, covering roughly 5.3GW of installed capacity and 4 million turbine days. The data were used to create pitch system reliability profiles for different regions, ranges of turbine rating and pitch system technologies.

The results of the benchmarking analysis were used as inputs for a study aimed at calculating the sensitivity of LCoE to changes in pitch system reliability, as discussed in Section 6 of this paper.

I. Data sources for Benchmarking Study

Different data sources were available to DNV GL for each of the 69 projects. These included owner reports summarizing component downtime, failure tracking logs summarizing component replacements, and fault logs from project SCADA systems.

From each project, DNV GL extracted the following data:

- Installed capacity
- Number of turbines
- Turbine rating (which for all projects was between 1.5MW and 3.0MW)
- Turbine pitch actuator technology (electric vs. hydraulic)
- Original equipment manufacturer
- Geographic region
- Data coverage in days
- Number of pitch system incidents for the whole wind farm
- Hours of downtime related to pitch system incidents for the whole wind farm

Depending on pitch system technology and on the terminology used in the different data sources, pitch system components included the following items: pitch motors, pitch drives, pitch batteries, pitch valves, pitch actuators, pitch cylinders/rams, pitch hydraulics, as well as the full pitch system. DNV GL extracted the relevant information from each source and combined the results into the analysis as explained in the following sections.

II. Definitions

In the scope of the benchmarking analysis, three metrics were calculated for each project using the collected data. They included:

1. Average availability losses (A_{vL})
2. Mean hours of downtime per pitch incident (MD)
3. Failure rate (number of pitch incidents per turbine per year) (RF)

The metrics are defined as follows:

$$A_{vL} = D / (NT \times LD \times 24)$$

$$MD = D / I$$

$$RF = I / (NT \times LD / 365)$$

Where:

D = total length of downtime in hours

NT = number of turbines

LD = length of data set in days

I = number of pitch incidents

Note:

- The availability loss definition includes all turbine-related downtime and does not consider any contractual carveouts.
- Downtime “incidents” were defined as events requiring any amount of unscheduled maintenance greater than 0.5 hours (i.e. where personnel may have attended the turbine). This definition includes both minor incidents (i.e. incidents requiring some maintenance but not full component replacement) and larger ones (i.e. incidents requiring component replacement).

- The analysis did not identify downtime events for other turbine components and therefore the total failure rate per project was not measured. For each of the three metrics listed above, filtering was applied to exclude outliers before calculating turbine weighted averages defined as follows:

$$XTW = \Sigma(Xi \times NTi) / \Sigma NTi$$

Xi is the project specific value of the metric being averaged and NTi is the number of turbines in that project. Turbine-day weighting was also considered but it was decided that it would give too much weight to old projects and therefore older technologies.

III. Failure Rate Findings

Average results for the failure analysis conducted by DNV GL are shown in Table 2. These values represent the failure attributable to pitch system incidents in the subset of data for which information was available. Results are similar across all regions.

A summary of pitch system failure rate findings by region, turbine size and technology are presented in Table 2 below. The number of projects reported in the table indicates how many projects constitute the data set. All results in the table are weighted by the number of turbines they represent.

The data aggregated in Table 2 illustrates two important points. Firstly, that pitch systems (both electric and hydraulic) are a major failure component in wind turbines. And secondly, that as turbine size increases so does pitch system failure rate.

	Failure rate ¹	Projects	Turbines
North America	0.6	23	907
China	0.7	3	30
Europe	0.9	19	393
All regions - 1.5 MW < X < 2.5 MW	0.5	38	1,136
All regions - 2.5 MW < X < 3.0 MW	1.6	7	194
All regions - Electric	0.69	18	545
All regions - Hydraulic	0.69	27	785
Overall	0.7	45	1,330

Table 2. Summary of Pitch System Failure Analysis Findings

¹ Incidents per turbine per year from projects with mean downtime > 3 hours

5 Pitch System Reliability Improvement Options

Moog develops and builds high performance pitch systems and pitch products for onshore and offshore wind turbines. Currently, more than 40,000 of Moog pitch systems and products are in operation in over 22,000 wind turbines worldwide.

In an effort to identify the greatest opportunity for pitch system reliability improvement, Moog evaluated three pitch system technology options. They included the following:

Electrohydraulic (EH) – EH pitch systems represent a mature technology, and as such, they have very limited opportunity for reliability improvement. Notable areas that contribute to lower reliability and high downtime factors in EH systems include rotary fluid joint wear, hydraulic fluid leaks, hydraulic fluid contamination, high maintenance, and high power consumption.

Electro Hydrostatic (EHA) – Electro Hydrostatic pitch systems are an attractive option for high-force applications; however, like EH systems, they offer little to no opportunity for reliability improvement.

Electromechanical (EMA) – Electromechanical pitch systems offer significant opportunity for reliability improvement through design optimization. This is largely due to the fact that current industry designs are based on components that were manufactured for general-purpose industrial applications with limited customization for wind turbines. Specific opportunities for reliability improvement include optimizing drive electronics by using pluggable PCB modules instead of wiring off-the-shelf DIN-rail components, using AC synchronous motor technology (brushless, no fans for cooling) to improve motor reliability and reduce periodic maintenance needs, and using ultracapacitors instead of batteries to eliminate backup power failures and periodic maintenance.

Technology Comparison

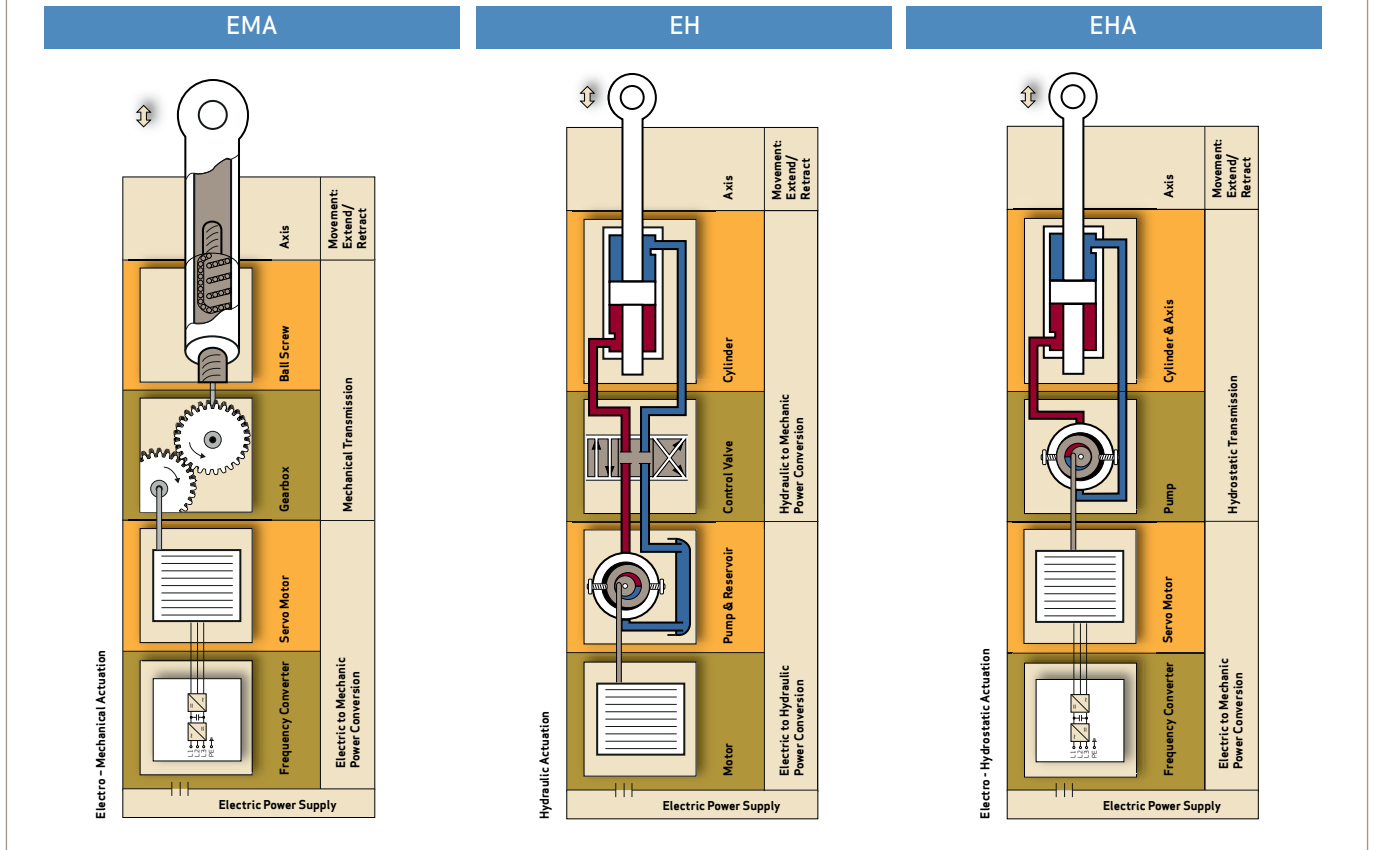


Figure 4. Moog Technology Comparison

Attribute	EM	EH	EHA
Compactness (size, weight and reduced part count)	+++	+	++
Design/Supply Chain Simplicity	+++	+	++
Control Quality	+++	+	++
Pre Tested Hardware	+++	+	++
Force Range	++	+++	+++
Ease of Maintenance	+++	+	++
Reliability	+++	+	+

Legend: + Improvements from Next Generation Technology
 + Current Industry Design

Table 3. Moog Design Improvement Options

I. Design Improvement Options

Based on the above analysis, Moog determined that electromechanical technology offers the greatest opportunity to improve pitch system reliability.

The majority of EM pitch systems currently being used throughout the industry are based on industrial grade multi-purpose drives with AC Induction or DC motors, which provide some level of customization for wind pitch control applications. The design itself consists of roughly 3,000 to 4,000 subcomponents. Field data collected for this study is a representative sample of this design.

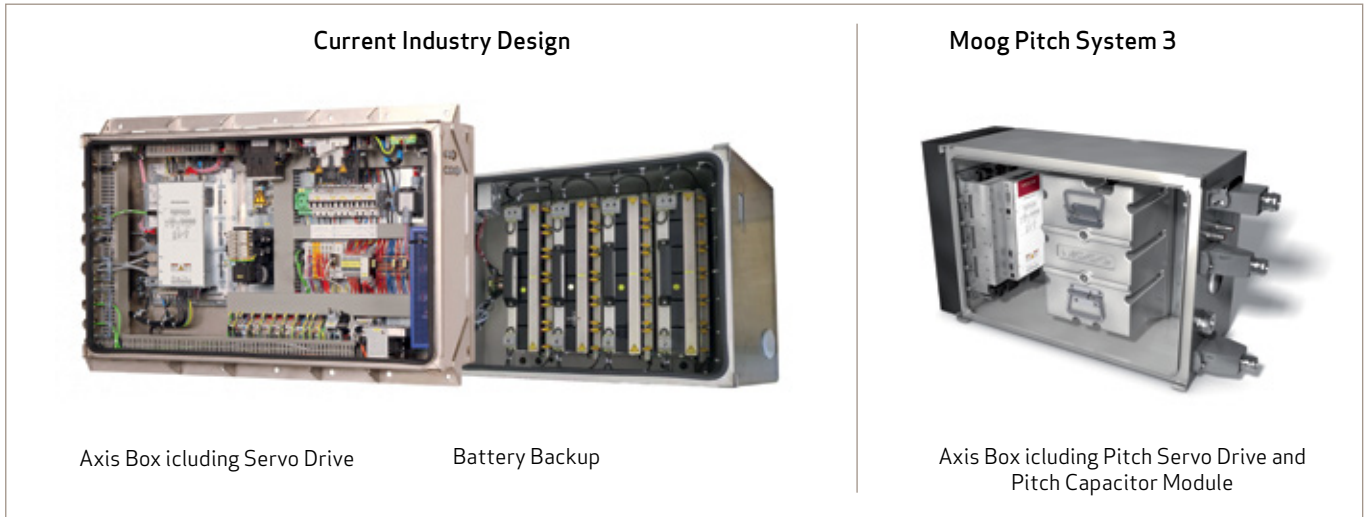


Figure 5. Moog Pitch System Profiles Used for LCoE Analysis

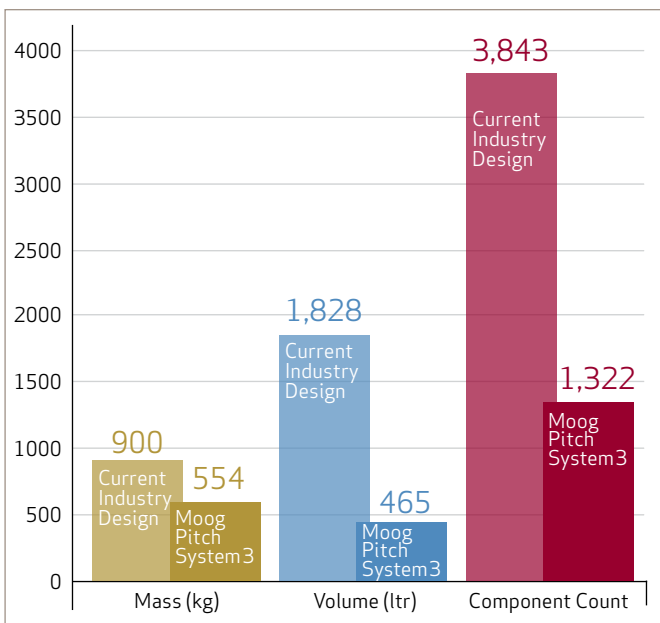


Figure 6. Pitch System Profiles Used for LCoE Analysis

Improved Pitch System Design – Moog developed a new design that is highly reliable compared to the Current Industry Design. The new design, released in 2016, offers the advantages outlined below:

a. High Reliability, Compact, and Lightweight:

- **Very high level of integration** of functional elements is made possible using pluggable PCB modules instead of wiring off-the-shelf DIN-rail components. (fewer components results in a decreased probability of failure / wiring errors and better control of manufacturing quality)

- **AC synchronous motor** technology (brushless, no fans for cooling)

The components inside traditional electric pitch systems used by the industry are based on commercially available, off-the-shelf technology components mounted on a DIN-rail. The new Moog Pitch System 3 design is based on a customized architecture with various components (drive, safety logic,...) that have been tightly integrated. The custom design allows for elimination of unnecessary features from standard components. Combining this design attribute with increased integration and fewer modules results in a highly reliable, compact and lightweight system, which conserves precious space in the tightly packed turbine hub.

b. Modular and Easy to Maintain

- **Star topology** with identical axis boxes
- **Standard interface**
- **Self-diagnostics** and **remote monitoring of core components** such as motors, drives and back-up

The new design eliminates discrete components with all key functional elements tightly integrated and connected by standard cable. Any malfunction in the system can be addressed by the field staff (no training required) by replacing the faulty box with a new drive. Wind farms can bring the turbine back online without requiring any specialized skills or resources, making it easier to maintain.

c. Scalable (one size fits all)

- Core components are optimized for high peak and low continuous power
- Scalable to different turbine sizes – avoiding creation of variants for turbines up to 3 MW class

The new system power needs are designed for normal continuous operation. During the feathering operation, the system draws the additional power required from the capacitance system. This is made possible by the intelligent interface between the drive electronics and capacitor block. By scaling the capacitor specification in line with the peak power needs of a turbine, the new system can be applied for a wide range of turbine models. Design improvements such as long blades do not require pitch system redesign, thus allowing OEMs to retain their hub design investments.

6 Moog Pitch System Levelized Cost of Energy (LCoE) Analysis

Using the findings of the benchmarking study presented in Section 4 as inputs, DNV GL carried out an analysis to calculate the sensitivity of LCoE to changes in pitch system reliability. DNV GL also calculated LCoE for a number of pitch system reliability profiles provided by Moog, including the new optimized design. The study made use of two DNV GL modeling tools (Turbine.Architect and OMCAM) to calculate CapEx, OpEx, and finally, LCoE based on pitch system profiles provided by Moog.

Turbine.Architect is a cost model tool for conceptual design and analysis. It can be used to study a wide range of input parameters and their influence on turbine CapEx, farm CapEx, energy capture, OpEx and LCoE. OMCAM was originally developed in 2006 and provides owners and operators with accurate estimations of future project O&M costs and turbine availability for a particular O&M strategy.

CapEx and OpEx for the different reliability profiles were calculated assuming:

- Upwind, Horizontal Axis Wind Turbines (HAWT), equipped with a DFIG with a partial converter, and a 3-stage gearbox.
- A 50 turbine wind farm, with site conditions corresponding to IEC class IIA
- A capacity factor of 0.35

Each pitch system was assumed to consist of one inverter, one motor, one backup unit and one controller.

I. LCoE Calculation

LCoE was estimated by Turbine/Architect as:

$$LCoE = (FCR \times CAPEX + OPEX) / AEP$$

Where FCR is the fixed charge rate applied to the CapEx – i.e. the annual cost to finance the CapEx – and AEP is the annual electricity production by the farm. FCR depends on the discount rate r (the sum of inflation rate and real interest rate) and on the number of years N over which the loan runs.

$$FCR = r / (1 - (1+r)^{-N})$$

The values assumed in the study were $r=0.11$ and $N=20$, resulting in a FCR of 0.125.

II. LCoE Analysis Results

The LCoE analysis showed that, when extreme cases are taken into consideration (i.e., for the same scenario, the differences between projects with "best" and "worst" performance in terms of pitch system failure rates), pitch system reliability can account for differences of up to 2 % in wind farm availability, 20 % in wind farm annual OpEx and 4 USD/MWh in LCoE.

When considering the reliability profiles provided by Moog, the LCoE analysis shows that the reduction in part repair time and failure rate (with respect to current design levels) obtained with advanced design can result in LCoE reductions of approximately 1.70 USD/MWh.

The main contributor to the reduction in LCoE in the above analysis is the decrease in unscheduled O&M expenses. This figure does not include savings from a reduction in scheduled maintenance activities due to electric pitch technology (vs. hydraulic), AC servo motor (vs. DC motor) or ultracapacitors for back-up (vs. batteries).

7 Conclusions

Overall, the results of the benchmarking study and LCoE analysis outlined in this paper illustrate two important points. First, that the average failure rate of pitch systems for onshore turbines between 1.5MW – 3.0MW is high (0.7 failures per turbine per year). And secondly, that by reducing part count and complexity and optimizing pitch system design architecture, reliability can be increased and OpEx associated with turbines can be reduced. For a typical 3MW turbine, improving reliability from current industry level (about 6000 hours MTBF) to 18,743 hours can result in \$1.70/MWh savings in LCoE (calculated using DNV GL's LCoE model).

Design	LCoE [USD/MWh]	Availability	Annual OpEx	LCoE Savings [USD/MWh]	System Reliability MTBF (hours)	Predicted number of failures in 20 years
Current Industry Design	53.31	-	-	-	5,769	30.4
Moog Pitch System 3	51.61	+1.2%	-8.2%	1.70	18,743	9.4

Table 4. Moog Pitch System Design Improvement Savings

8 Resources

- 1 <http://www.gwec.net/global-figures/graphs/>
- 2 Tavner, P J (2012). Offshore Wind Turbines-Reliability, Availability & Maintenance

Bloomberg New Energy Finance

www.moog.com/wind

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