US Energy Sources For Electric Power Generation and Wind Turbine Reliability Problems

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It has been predicted that the United States will face unprecedented challenges with respect to the supply of reliable electric power to various parts of the country this coming summer. For example, California last summer had rolling blackouts and now it has been predicted that this will also occur in other regions of the country such as the Midwest, Southwest and even in some regions of New England. The reasons for this are complex; but essentially the main causes for this to occur is the climate change with elevated temperatures, drought, most important, the reduction of reliable electric power sources and the fragile electric power grid.

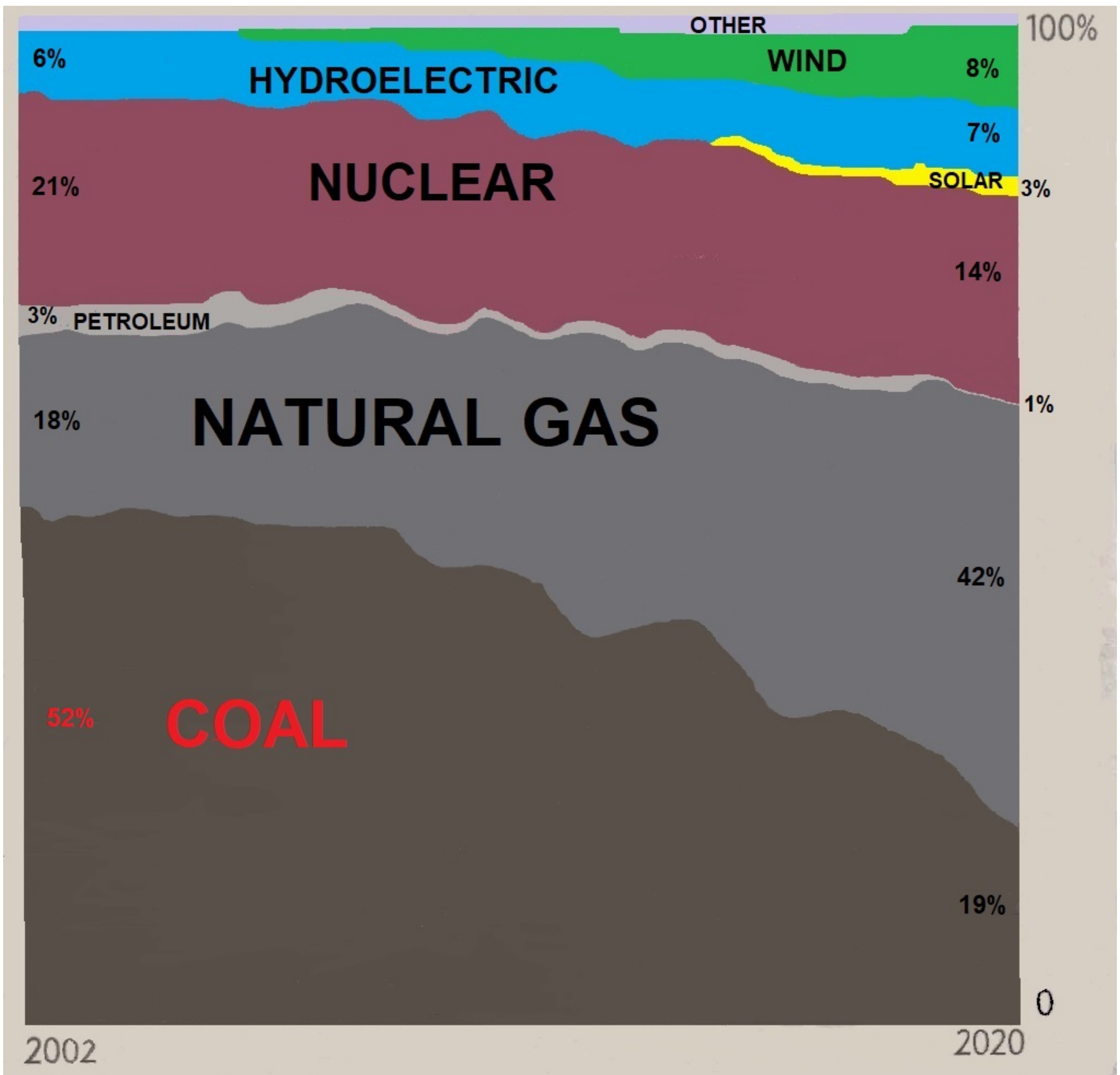


Figure 1 Power Generation Energy Sources From 2002 To 2020
(James Benedict WSJ 1/19/2022)

Summary of US Energy Sources From 2002 to 2020 & 2021

In February, 2022, the Wall Street Journal published an extensive article on the uses of various energy sources in the United States as shown in Figure 1. A summary of the various sources of energy used for power generation for the entire country are shown as follows:

Electric Power Energy Sources From 2002 To 2020 *(WSJ)* and 2021*(US Gov)*[1]

Energy Sources	2002	2020	2021
Coal	52%	19%	22%
Natural Gas	18%	42%	***38.3*** %
Petroleum	3%	1%	0.5%
Fossil Fuels	***73 %***	***61*** %	***60.8*** %
Clean Energy			
Nuclear	21%	14%	***19*** %
(Renewable Energy)			
Hydroelectric	6%	6.3%	6.3%
Wind	0%	8 %	9.2%
Solar	0%	2.8%	2.8%
Biomass	1%	1.3%	1.3%
Geothermal	0%	0.4%	0.4%
	7%	***18.8%***	***20%***

Brief Summary: ***20 % Renewable Energy in 2021, Wind & Solar - 12 %***

It is seen from the above chart that since 2002, the use of fossil fuels for electric power generation has decreased from 73% to less than 61% by 2021. In particular it is seen that the use of coal for power generation has had a dramatic reduction from over 50% in 2002 to 22% in 2021 as reported by the US Government[1].

The WSJ article also shows that the use of natural gas increased significantly from 18% in 2002 to 42% in 2020. What is of particular concern is that the use of natural gas one year later, as reported by the US government, reduced from 42% to 38.3%. This ***10.9 %*** reduction in natural gas usage appears to be directly related to the efforts of the current Biden government to wean our way from all fossil fuels, including natural gas.

A good example of this effort to diminish the use of natural gas can be seen by the stoppage of the gas pipeline from West Virginia to Virginia. This pipeline is of critical importance now that the demand for natural gas has gone up significantly due the war in the Ukraine. Another unfortunate occurrence with the expansion of natural gas usage is with the blockage of the development of new LNG facilities by our current administration for the export of liquefied natural gas.

One striking example on energy development, is that in 2021, solar energy is less than 3% of the energy for power generation and wind turbine power generation is slightly more than 9%. The reason for this stagnation in the development of solar and wind energy is due to the significant pushback by local communities for installing solar and wind turbines in their community. In 2021 alone, 31 wind turbine projects were blocked by local communities and 13 large solar projects were also blocked or delayed[2].

(1) WWW.eia.gov>electricity

(2) WWW.RobertBryce.com

The Future of Clean Renewable Electric Power from Wind Mills

The total US electric power produced by both land and off shore wind turbines, in all probability, will never exceed 20 % of electric power generation, regardless of the number of wind turbines installed! The reason for this bold statement is twofold:

First, has been the considerable rejection of wind turbines by communities in both in the United States and Hawaii. Since 2015, 320 wind turbine projects have been delayed or completely rejected.[(2)]

Second, is the fact that these wind turbines are highly unreliable from a mechanical standpoint. More on this will be explained in detail later. Maintenance costs, particularly for offshore wind turbines will be astronomical. Bearing failures can occur in less than one year.

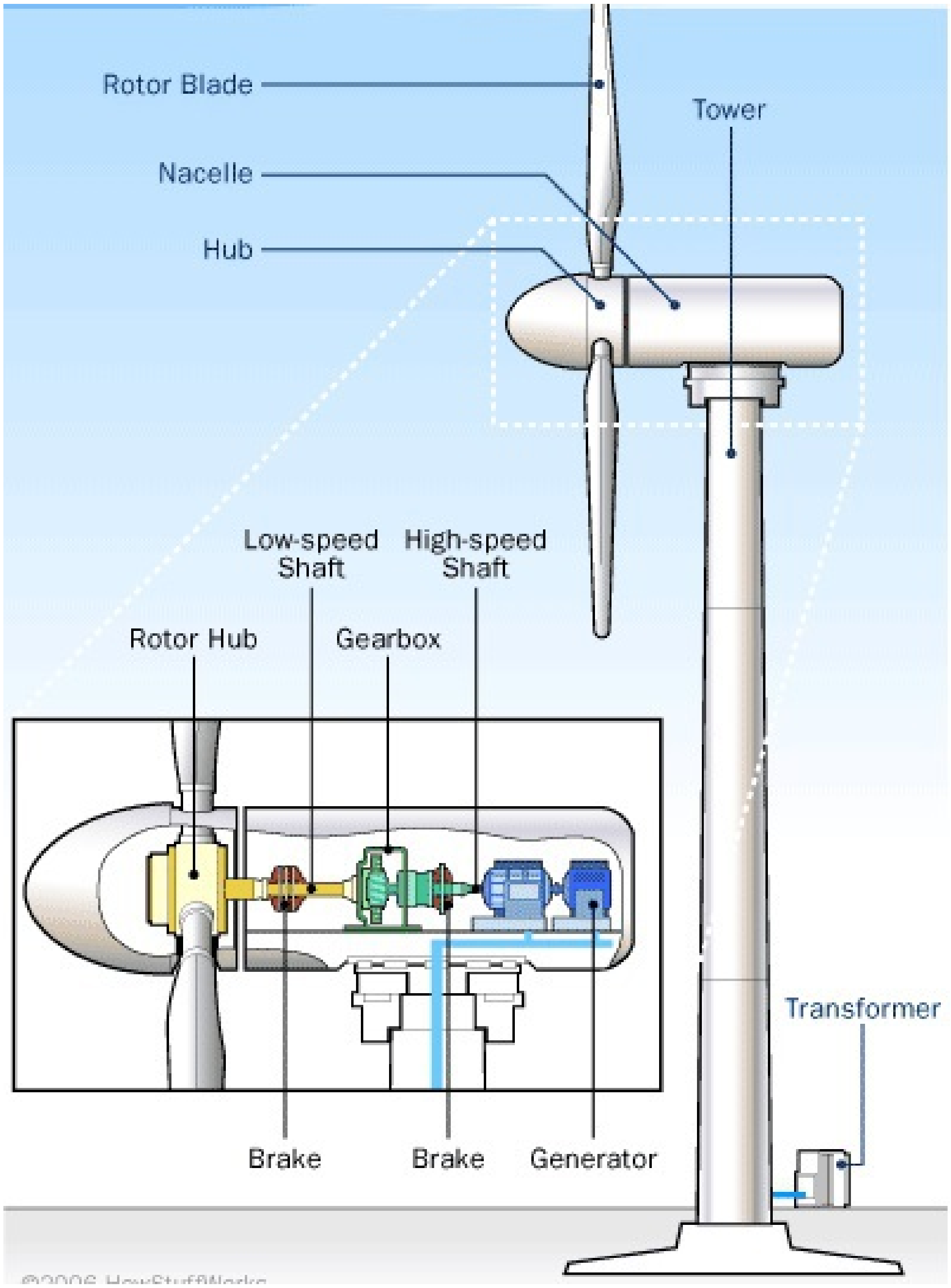


Figure 2 Schematic of A Typical Commercial Wind Turbine

Figure 2 represents a schematic of a typical commercial wind turbine and drive system.
The new offshore GE Haliade 13MW turbine will stand 260 m (850 ft) with 107 m blades.

The very low fan rotational speed of about 20 RPM must eventually be converted by a gear system for a generator operating at 1200 to1800 RPM for 60 cycle electrical power. The European wind turbines run at a slower speed as the electrical standard is 50 cycles.

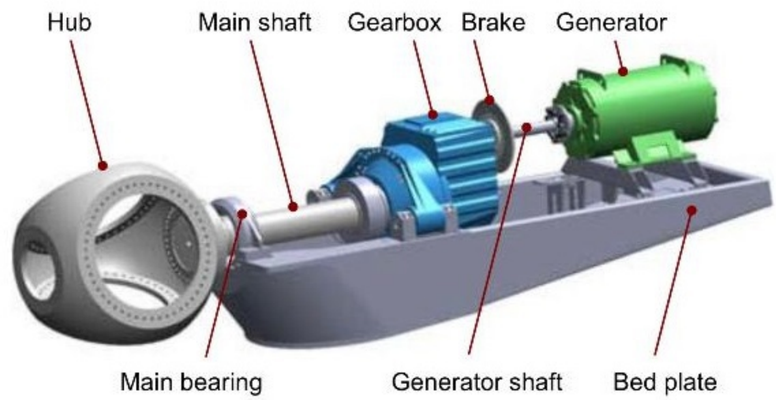


Figure 3 Typical Utility Wind Turbine Drive System
S. Sheng & P. Veers, Wind Turbine Drivetrain Monitoring
Mechanical Failures Prevention Group Conf; Virginia Beach, VA 2011

Figure 3 shows a typical utility wind turbine drive system as presented by Sheng and Veers at the annual Mechanical Failures Prevention Group Conference held at Virginia Beach in 2011. The reason for the presentation of the conference on the wind turbine drive systems was because of the gearbox and bearing reliability issues of these wind turbines.

In the last 2 decades, wind turbines have increased considerably in both size and power. However, this increase in the size of these wind turbines has not been accompanied by a proper dynamic analysis along with advanced vibration instrumentation to understand the dynamic loading on the turbine drive system. The stated life of these wind turbines is stated as 20 years, in comparison to sixty years for a modern small nuclear power system currently designed for the power utility industry.

Bearing failures have been reported in as little as one year with these large wind turbines. Major maintenance issues are expected to be a yearly issue with the gear box bearings, gearing and also with the main load carrying fan bearing.

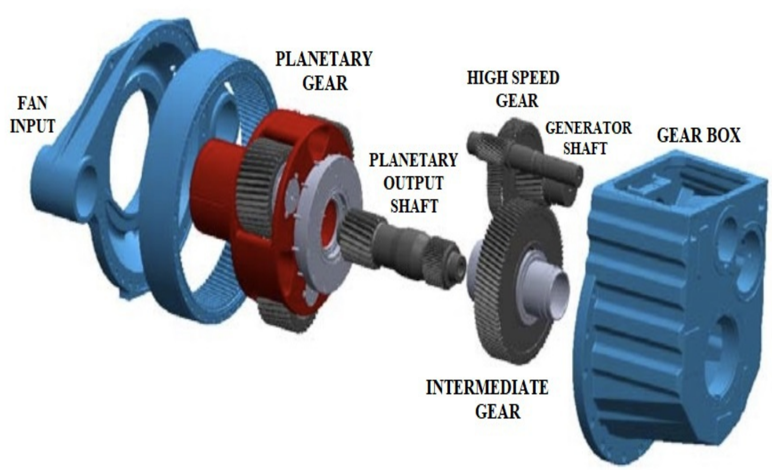


Figure 4 Components of Wind Turbine Drive System
S. Sheng & P. Veers, 2011

Figure 4 represents the gearbox configuration, also taken from the Sheng and Veer paper with the addition of labeling of the major components.

As can be seen, the drive system for a wind turbine is considerably complex, with the low-speed fan input shaft first going into a planetary gear system.

The output of the planetary gear system is connected to an intermediate gearing, and then a second high-speed gear output is used to drive the generator at either 1200 or 1800 RPM. The research into the reliability of wind turbine gearbox systems has been led by the US Government NLRE (National Laboratory for Renewable energy) Organization. In 2007, NREL initiated the Gearbox Reliability Collaborative (GRC) to understand causes of failure. To date, they have made little progress in understanding principal causes of failure.

In previous meetings supported by the NLRE, the conference participants could not explain why there was such a rate of bearing and gear tooth failures in these gearboxes, and as to whether this was a material or a lubricant problems. In addition to failures of gear box components, there occurred also failures of the main fan bearing and generator bearings.

The basic problem is that the organization does not understand the basic forces and dynamics occurring with these systems. It has just recently come to instrumenting a typical gearbox to examine the vibration spectrum with accelerometers. Figure 5 for example, represents a typical spectrum obtained from one of the accelerometers on a test gearbox.

The wind turbine industry in general, is 30 years behind the dynamic testing of their wind turbines as compared to the petroleum (API) and power utility industry. The use of accelerometers, for example, provides only a limited range of useful information to understand proper dynamics of a complex system. For example, the forces generated at low speeds, such as caused by the fan, can not be properly evaluated by accelerometers.

The higher frequencies, as shown in Figure 5, are of little significance as there is very little energy in these modes to cause damage to the gearbox.

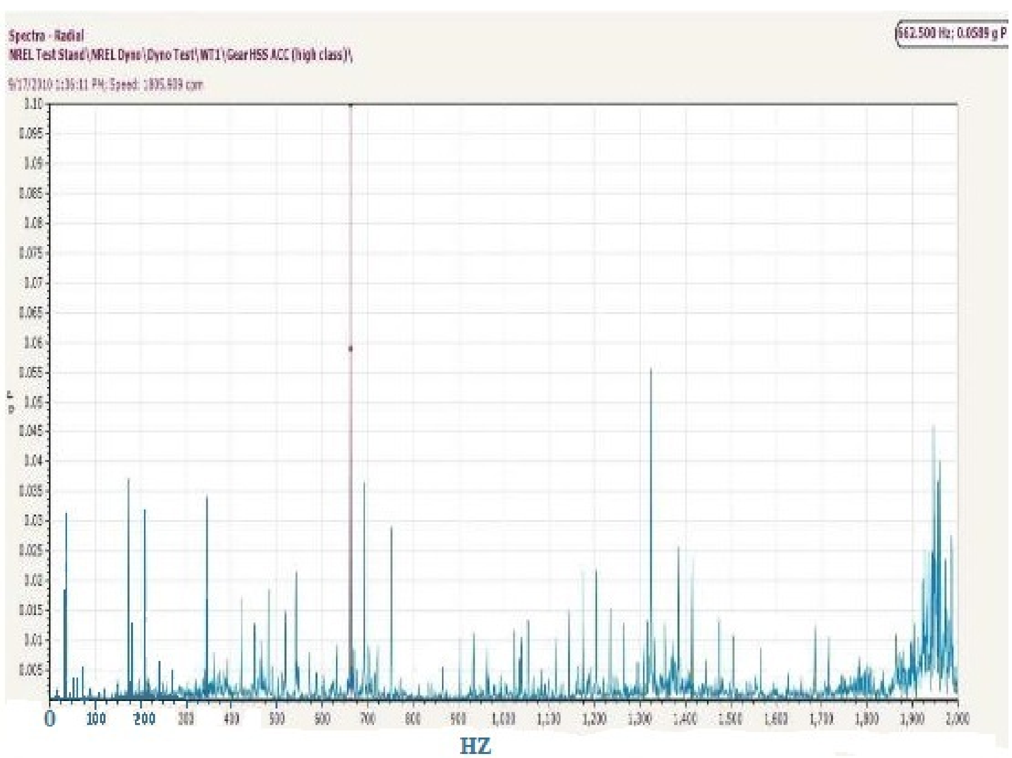


Figure 5 Accelerometer Frequency Spectrum of Wind Turbine Drive System
S. Sheng & P. Veers, Wind Turbine Drivetrain Monitoring
Mechanical Failures Prevention Group Conf; Virginia Beach, VA 2011

Comparison of Wind Turbine Design to Conventional Utility Turbine-Generators

It was stated in the paper by Sheng and Veers that it was unknown as to why various wind turbine bearings should fail so rapidly, in some cases less than one year. The reason is quite simple. Conventional power utility turbine-generators do not use rolling element bearings! All conventional turbine-generators use fluid film bearings. The advantage of the fluid-film bearings is that they provide damping to control critical speeds and transient rotor response. Large utility power plants, for example, rolling element bearings are only used in some pumps and in some induced air fans.

The reason rolling element bearings are never used in conventional power plant turbine-generator systems is because of the lack of damping in the rolling element bearings to control critical speed response and the resulting bearing forces transmitted. The life of rolling element bearings are very sensitive to the loading applied. For example, a doubling of the load on a rolling element bearing reduces its life by a factor of eight fold! Technically stated, the L10 life of a rolling element bearing is inversely proportional to the cube of the bearing loads.

An example of the limitation of the operating life with a unit using rolling element bearings is the space shuttle oxygen pump. This oxygen pump was designed with a 55 mm ball bearing at the main pump impeller and a 45 mm bearing at the preburner location. The original design life of the oxygen pump was supposed to be eight hours. Because of the loading on the preburner bearing due to operation near the second critical speed, the bearing preburner life was only eight minutes![(3)]

Failure of the preburner bearing in the oxygen pump resulted in a catastrophic pump and test gantry failure as the steel pump casing itself ignited due to the dense consentration of liquid oxygen. In one case, a 11 story test gantry was destroyed due to failure of the preburner bearing. The problem was eventually solved by changing the preburner labyrinth seals to a stepped seal design to provide improved damping[(3)].

In the case of the design of the windmills, there is no bearing damping present to attenuate the various lateral and torsional critical speeds encountered with these units. It was also observed that in addition to failure of the gearing bearings, there was also failure of gear teeth in the planetary gear box. The presence of gear tooth damage and failures is evidence of the existence of torsional vibrations. The presence of torsional critical speeds with these wind mills can not be avoided.

Conventional power turbine-generators are directly coupled and designed to run at a constant speed. For lower power 100 MW gas turbines with 2 pole generators, the speed is 3,600 RPM for 60 Hz current in the US. For the larger utility 500-1000 MW systems, the speed is 1200 or 1,800 RPM for 6 and 4 pole generators. In Europe, both power equipment and windmills will run at a lower speed since Europe is based on a 50 Hz electrical system.

The wind turbine design as shown in Figs. 2-4 has two significant mechanical design faults which will severely limit the useful life of these turbines and, in addition, lead to excessive maintenance costs over their short life span. These design faults are, first, the use of over 12 rolling element bearings in the system. As previously stated, this type of bearing is never used with conventional power generation equipment because of the limited life of rolling element bearings and also the important feature that these bearings have no damping! The ball bearing life can not be improved by a change of lubricant, material property or surface coating or treatment. All conventional power generation equipment uses fluid film bearings because of superior damping for critical speed control.

(3) Dynamic Characteristics and Stability Analysis of Space Shuttle Main Engine Oxygen Pump, E. J Gunter, MFPG, 1989.

The second serious design flaw in these wind turbines as shown in Figure 2, is the presence of a speed brake installed between the fan shaft and the gearbox. This brake is required to control the fan speed under high wind conditions. The use of a speed brake to slow the fan down is totally unacceptable for use in a power generation system. The reason for this is that the braking action on the fan causes large torsional vibrations between the fan, gearbox and the generator. It has been reported that gear teeth have been broken.

The failure of gear teeth and shaft failures is a further indication of the existence of torsional critical speeds. Power utility equipment is meant to run at a constant speed. If there is a small fluctuation in speed or deviation from 60 cycle current, torsional excitation from the generator can also develop at a frequency of 120 Hz for American equipment and100 Hz for European generators. The existence of a speed brake in a wind turbine is a further example of a design feature that will drastically limit the useful life of these turbines.

Improved Instrumentation for Bearings and Gearbox Failure Evaluation

In order to determine the causes of the various failures encountered with gearbox bearings and teeth, 12 accelerometers were set up on an experimental gearbox by NREL in an effort to evaluate the causes of component failures. As can be seen from the spectrum as shown in Figure 5 for one of the accelerometers, there are a number of significant vibration components excited in the gearbox. The use of accelerometers to measure the vibration spectrum indicates there are a significant number of resonance frequencies existing in the gearbox, but the accelerometers do not provide information as to what components are involved or what the corresponding mode shapes are.

In particular, the use of accelerometers is of no value in determining the bearing forces exerted by the fan on the main fan bearing. In order to determine the forces exerted on the fan bearing, a calibrated support structure would need to be designed similar to that used in a hard bearing balancing machine. This support is calibrated with strain gauges to measure the forces transmitted. Significant bearing forces can be exerted by the fan, even though it is rotating at a relatively slow speed. Significant fan unbalance forces may occur during operation due to fan blade erosion and buildup of ice under winter conditions. Hence, extensive forces may be exerted on the fan bearing causing premature failure. At present, windmill designers have not been able to evaluate the actual main bearing forces transmitted by the fan during operation under severe weather and wind conditions.

The failure of gear teeth indicates the presence of torsional oscillations. In order to evaluate torsional oscillations, torsional strain gauges need to be applied to the high-speed shaft connecting the generator. The API code details the use of these strain gauges for torsional operation.

The high-speed shaft also needs to have noncontact proximity probes installed in order to measure shaft amplitudes at the generator location. Also required with noncontact probes would be a key phasor probe for measurement of phase and for synchronous tracking of rotor motion. Until proper instrumentation is applied to the gearbox, the source of the vibration and loads transmitted to the various bearings will continue to be a complete mystery.

One conclusion that can be made is that the reliability of the gearbox and bearings cannot be improved simply by a change of lubrication or gearing or bearing material properties. Figure 5 shows that these windmills have significant rotor bearing dynamic vibration modes which have resulted in premature failure of various components.

The Future Of Offshore Wind Turbine Farms

A key component of the WWS (***Wind, Water, and Solar***) 100% Renewable Clean Energy Program is use of wind turbines. A further discussion will be presented later to review in more details the WW S 100% Clean Energy Program which claims that it does not require the use of ***fossil fuels*** or ***nuclear energy*** to achieve 100% clean, renewable energy by 2050.

The current emphasis now in the development of the renewable clean energy program, is the expansion of offshore wind turbine farms using the latest of high MW turbines currently being developed. The reason for this is that offshore ocean winds are much stronger than the onshore winds, and hence much larger and more powerful wind turbines may be situated in large wind turbine farms for electric power generation.

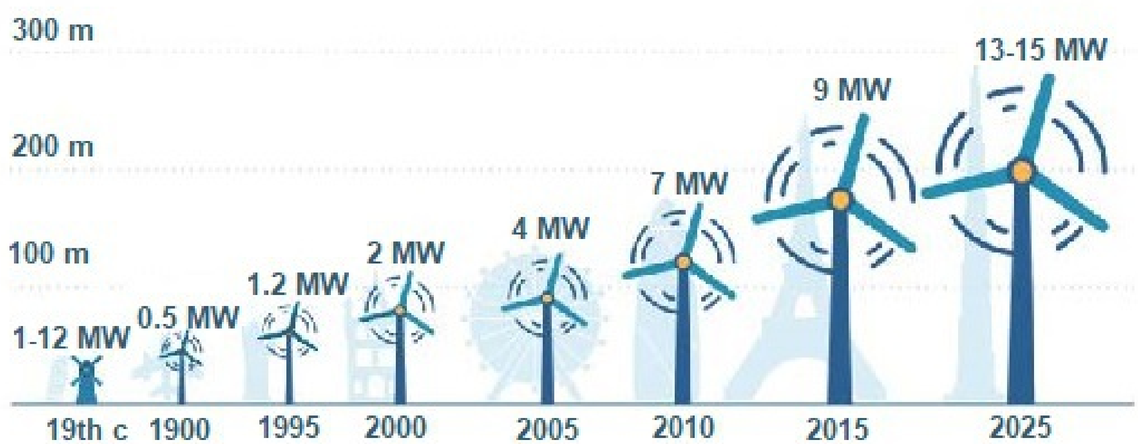


Figure 6 Change in Wind Turbine Power And Predicted Future Turbine Power Levels
(IRENA 2021)

Figu re 6 shows the steady increase of power in offshore wind turbines from the 19th century to the present. It was predicted in 2021 by IRENA ***(International Renewable Energy Agency)*** that by 2025 that wind turbines would achieve power outputs of 13 to 15 MW. That situation has already been achieved by various wind turbine manufacturers. For example, GE has developed the Haliade X turbine with a capacity of 13 MW.

This GE wind turbine will be used in the Vineyard Wind Project using 62 GE Haliade X 13 MW turbines. The projected cost is assumed to be $8.3B. This translates to approximately $134 M per/turbine. This project will be located approximately 15 miles off the coast of Massachusetts. The stated purpose of the project is to generate clean, renewable, affordable energy for over 400,000 homes and businesses across the Commonwealth, while reducing carbon emissions by over 1.6 million tons per year.

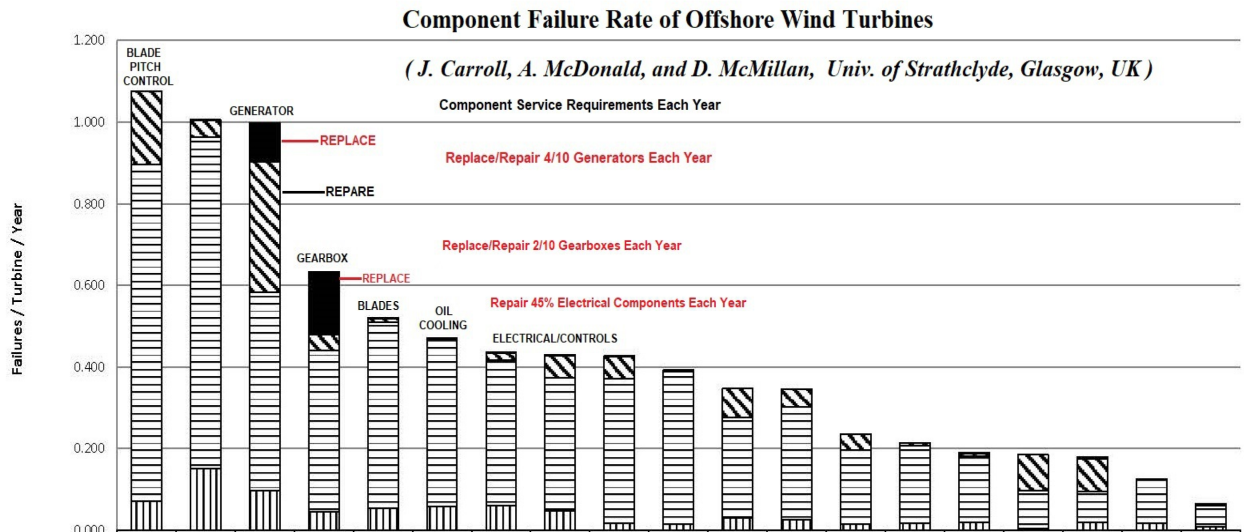
Later in this section, the question as to whether this is truly affordable energy will be addressed. It will be shown that wind turbine farms have had massive reliability problems in maintenance of the equipment which have lead to excessive operating costs. These operating costs will skyrocket with the larger wind turbines being proposed.

It will be seen that all offshore wind turbines are highly unreliable both with the mechanical and electrical equipment. The stated life of these wind turbines is given as 20 years as compared to 60 years for the new small nuclear power plants. A stated wind turbine life of 20 years is misleading because, as an extensive UK study completed in 2015 on 350 offshore wind turbines, showed that every year, 8.3 service calls are required on the average. After3 years of operation, each wind turbine required 10 service calls! These were for the 2-4 MW units used at the time.

UK 2015 Offshore Wind Turbine Failure Rate

The development of offshore wind farms has proceeded in Europe at a fairly rapid pace. However, due to the many failures and repairs required with the offshore wind turbine farms, the British Government Engineering and Physical Research Council awarded the University of Stratheclyde's Wind Energy Systems Centre a grant for the study of the failures and repairs required on offshore wind turbine farms.

A study of 350 wind turbines from various manufacturers with power ratings from 2 to 4 MW was conducted over a five-year period. An extensive report was issued in 2015 concerning their findings[(4)].



	Pitch / Hyd	Other Components	Generator	Gearbox	Blades	Grease / Oil / Cooling Liq.	Electrical Components	Contactor / Circuit Breaker / Relay	Controls	Safety	Sensors	Pumps/ Motors	Hub	Heaters / Coolers	Yaw System	Tower / Foundation	Power Supply / Converter	Service Items	Transformer
Major Replacement	0.001	0.001	0.095	0.154	0.001	0.000	0.002	0.002	0.001	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.005	0.000	0.001
Major Repair	0.179	0.042	0.321	0.038	0.010	0.006	0.016	0.054	0.054	0.004	0.070	0.043	0.038	0.007	0.006	0.089	0.081	0.001	0.003
Minor Repair	0.824	0.812	0.485	0.395	0.456	0.407	0.358	0.326	0.355	0.373	0.247	0.278	0.182	0.190	0.162	0.092	0.076	0.108	0.052
No Cost Data	0.072	0.150	0.098	0.046	0.053	0.058	0.059	0.048	0.018	0.015	0.029	0.025	0.014	0.016	0.020	0.004	0.018	0.016	0.009

Figure 7 UK 2015 Offshore Wind Turbine Component Failure Rate
(J. Carroll, A. McDonald, & D. McMillan, Univ. Of Stratheclyde, 2015)

Figure 7 shows a summary chart of the repair and replacement issues with the various components on the offshore wind turbines. The repairs were listed in three categories as minor, major and replacement. The largest category involved repairs were on the propeller pitch and hydraulic systems. A large majority of these problems were listed as minor.

However, the most serious and expensive components were involved with the gearbox and the generators. For example, with the gearboxes, two out of every 10 turbines had a major repair or replacement. Two important categories that did not appear with the onshore wind turbines was the repair rate on the generators and also on the electrical system components. The repair of the electrical systems was much more extensive than what was encountered on onshore wind turbines. With respect to generators, it is seen that 4/10 generators had to be have major repair or replacement each year.

Note that 45% of the electrical equipment has to be repaired each year on the offshore wind turbines.

(4) Failure Rate, Repair Time and Unscheduled O&M Cost Analysis of Offshore Wind Turbines
J. Carroll, A. McDonald, and D McMillan, University of Strathclyde, Glasgow, UK, 2015

Generator and Electrical Component Failure Rates for Offshore Wind Turbines

It was found that with the offshore wind turbines, significant problems were encountered with the generators that were not encountered with the onshore-based units. The reason for this appears to be the salty ocean environment, causing corrosion not only of the generator, but also of other electrical components. Figure 8 represents a comparison of the minor, major repair and replacement rates of the offshore generators as compared to the onshore units.

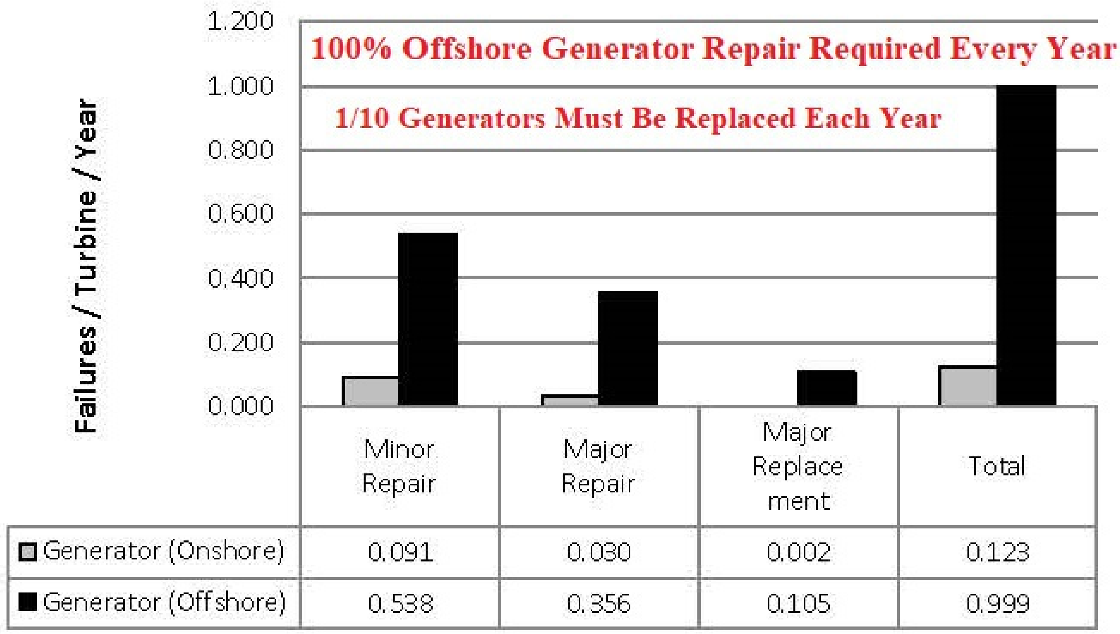


Figure 8 Comparison of Offshore and On Shore Generator Repair and Failure Rates
(J. Carroll, A. McDonald, & D. McMillan, Univ. Of Stratheclyde, 2015)

The onshore generators appeared to be fairly reliable, but this is not the case with generators exposed in a salty ocean environment. Efforts have been made to seal the wind turbine nacelle from the environment, but this has proven to be difficult. In the report, it was shown that on the average, 8.3 service calls were required for every turbine each year. After a three year period, an average of 10 service calls were required per turbine. Thus, adequate sealing of the nacelle from the elements was not effective in preventing damage and corrosion due to the ocean environment.

The US Government formed the NREL to primarily investigate the failure rate of gearboxes of the onshore wind turbines. It now appears that with the larger offshore units being installed, such as the GE Haliade X 13 MW turbines, generator and electrical problems will now also be of great significant, in addition to gearbox and main bearing failures. The GE Haliade X 13 MW turbines are scheduled for use in the Vineyard Wind Project with the installment of 172 turbines for a project cost of $8.3B.

Some Fundamental Problems with Both Onshore and Offshore Wind Turbines

1. **Wind Reliability**

The most significant problem with both onshore and offshore wind turbines is the unreliability of the wind. Wind turbines have been placed in offshore locations because of the high volume of usually reliable air. However, Germany experienced problems with their offshore wind turbines with a period in which the wind did not blow.

In the western part of the United States during a high heat spell, wind turbines, particularly in the Texas area, did not receive any wind at all. Texas is receiving 30% of its energy from wind turbines. A one point, the wind turbines were generating too much power! Since the Texas power grid is independent from the US grid, the turbine were ordered to shut down as there is no way to store the energy. The new large capacity utility lithium batteries have shown to be easily able to catch on fire and are difficult to extinguish.

Denmark found out that no matter how many wind turbines you have, you still need to have the same amount of base power because of the unreliability of the wind.

2. **Mechanical and Electrical Reliability**

The basic mechanical design of wind turbines has caused considerable mechanical reliability problems, particularly in the bearings and gearbox. Unlike conventional turbine-generators which have well damped fluid film bearings, the typical wind turbine may have up to 12 rolling element bearings with essentially no damping. It has been seen that internal wind turbine bearings may fail in as little as one year of operation.

Wind turbines also cannot operate in high wind conditions. Therefore, mechanical brakes have to be used to control the speed of the wind turbine. During high wind conditions, the turbines need to be completely shut down. These mechanical brakes can lead to torsional vibrations in the wind turbine, leading to gearbox tooth and generator shaft failures.

Electrical problems with offshore wind turbines have been particularly severe with the electrical connections and the generators due to the salt air environment. Earlier studies of offshore wind turbines, for example, have shown that after several years of operation, up to 10 service calls per year may be required for each wind turbine.

3. **Limited Useful Service Life**

A typical utility power plant has a service life of aproximately 40 years. The new, small modular nuclear reactors are predicted to have a service life of 60 years.

It has been stated that the wind turbines will have an approximate life of 20 years. This apparently will not be the case as it has been seen that wind turbine blades, particularly in offshore use, have to be replaced within 12 years. Thus, replacing offshore wind turbines after only 12 or 15 years of operation, will be a monumental task and incredibly expensive.

4. **Connection to the Power Grid and Electric Reliability**

Connection of wind farms in the United States to the electrical grid has been a challenge. Wind farms are typically located in isolated locations in which it is not easy to connect to the electrical grid. The problem with connecting offshore wind turbine farms is extremely challenging as the cables must be laid securely so that they do not interfere with shipping and damage from ships anchors.

Another significant challenge for wind turbines is the synchronization of the frequency with the power grid. This presents a challenge due to variable speeds encountered with the wind turbines. Variable line frequencies can lead to 2x60 Hz torsional excitation of generators.

Resume

Edgar J. Gunter, PhD

Dr. Gunter is a retired Prof. of Mechanical and Aerospace Engineering at the University of Virginia. He received his Mechanical Engineering degree from Duke University and Masters and PhD degrees from the University of Pennsylvania in Engineering Mechanics.

He was employed as a centrifugal compressor design engineer for four years at Clark Brothers, Olean, New York, now a division of Dresser-Rand. Based on his compressor design projects, he was awarded a National Defense Fellowship to pursue the PhD degree in Engineering Mechanics.

During his graduate studies, he received an internship with the SKF Ball Bearing Research Center to study fatigue life of rolling element bearings. In his graduate program, he majored in applied mathematics, vibration and dynamics, fluid mechanics and lubrication theory.

After completing his formal training at the University of Pennsylvania, he assumed the position of Senior Research Scientist at the Franklin Institute Friction and Lubrication Laboratories in charge of the Gas Bearing Division. While at the Franklin Institute, he received a NASA Lewis Research Grant to study rotor - bearing stability. The study was initiated since at that time the Franklin Institute had some of the world's largest digital and analog computers at the Institute. The report on Rotor Bearing Stability was published by NASA as a special CR report and given national distribution. This report formed the basis of his PhD dissertation.

Upon receiving his formal PhD degree, Dr. Gunter was then offered the position of tenured Associate Prof at the University of Virginia. At the University of Virginia, he developed the Rotor Bearing Dynamics Laboratory to assist industry in the development of reliable high-speed rotating equipment.

He has been elected to the following honorary engineering societies of Pi Tau Sigma, Tau Beta Pi and Sigma Xi. He was elected as a fellow of ASME in 1996.

In 2008, Dr. Gunter was awarded the first Jack Frarey Memorial Metal by the Vibration Institute for contributions to the field of rotor dynamics.