Wind Turbine Blade Structural Health Monitoring

Methods and Benefits

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ABSTRACT

Structural Health Monitoring (SHM) is the automated inspection and evaluation of structures such as wind turbine blades. This report examines the current state-of-the-art blade SHM systems, identifies future trends, and outlines a methodology for probabilistic cost-benefit analysis of the application of SHM systems to wind turbine blades.

The reliability of wind turbine blades is an ongoing concern for the wind industry. Applying SHM to blades may be one way to reduce blade failure rates and reduce the downtime associated with blade failures by mitigating the risk of undetected damage, which may result in failure of turbine blades and turbine systems.

To maximize usefulness to wind turbine operators and maintainers, SHM systems would ideally detect the presence, type, location, and size of damage in a blade. Numerous SHM systems exist that can meet some or most of these measurement objectives. The most common elements of modern SHM systems are described and summarized in the report.

The design and application of SHM systems to wind turbine blades is directly affected by the structural elements in the blade. These basic elements determine which areas require monitoring, and what the approach to monitoring will be. In order to provide background for how SHM systems may be applied to MW-scale wind turbine blades, this report presents some current trends in the design and construction of typical commercial blades.

SHM systems increase the initial capital cost of a turbine but may lead to positive future returns by informing decisions leading to decreased downtime. This report examines the estimated return on investment of an SHM system for a wind turbine blade. This study is unique in that an uncertainty analysis has been included in the SHM cost-benefit analysis.

While SHM systems are not currently widely deployed on wind turbine blades, the potential exists to increase turbine availability through the use of such systems. Multiple SHM techniques are available, and the suitable mix of technologies to meet the requirements for damage detection on blades is yet to be determined. However, low-cost SHM systems that increase wind turbine availability are likely to be commercially successful because of positive future returns on an initial investment in those systems.

Keywords
Wind Turbine
Blade
Structural Health Monitoring
Condition Monitoring

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1 INTRODUCTION

Condition Monitoring (CM) systems provide data for estimating the condition of machinery. CM data may be used to optimize machine operation, detect problems early, and inform maintenance practices. CM is currently widely deployed in the wind industry on wind turbine main bearings and gearboxes. Structural Health Monitoring (SHM), a subset of condition monitoring, is the automated inspection and evaluation of structures such as wind turbine blades.

In 2002, Risø published a comprehensive study of SHM for wind turbine blades [1], which included a survey of sensor types, a cost-benefit analysis, and test results. Since the Risø study was completed, further research has been conducted on SHM systems for wind turbine blades, wind turbine designs have increased in size and complexity, and applications of SHM systems to wind turbine blades have expanded. As turbines continue to increase in size, and offshore applications become more prevalent, the potential for SHM systems to offer benefit through reduction in downtime may also increase. Updated assessment of this potential is warranted.

In this study, we examine the current state of the art of blade SHM systems, identify future trends, and perform a probabilistic cost-benefit analysis of the application of SHM systems to wind turbine blades for offshore and onshore turbines. We begin with a brief discussion of the motivation for applying SHM to wind turbine blades.

Motivation

The reliability of wind turbine blades is an ongoing concern for the wind industry. Blades are expected to operate with minimal maintenance in a high-fatigue environment for a design life of 20 years, and are expected to be highly economical structures. Studies, including [2], have investigated actual failure rates of wind turbine components, including blades. Figure 1-1 shows failure frequencies and associated downtime for multiple components, including blades, from two studies. Relative to most other components, blade failures show a large downtime per failure. The relatively large downtime per failure illustrates the importance of reducing blade failure rates. In addition, a blade failure, if significant enough, may directly lead to additional damage to the turbine including component failures.

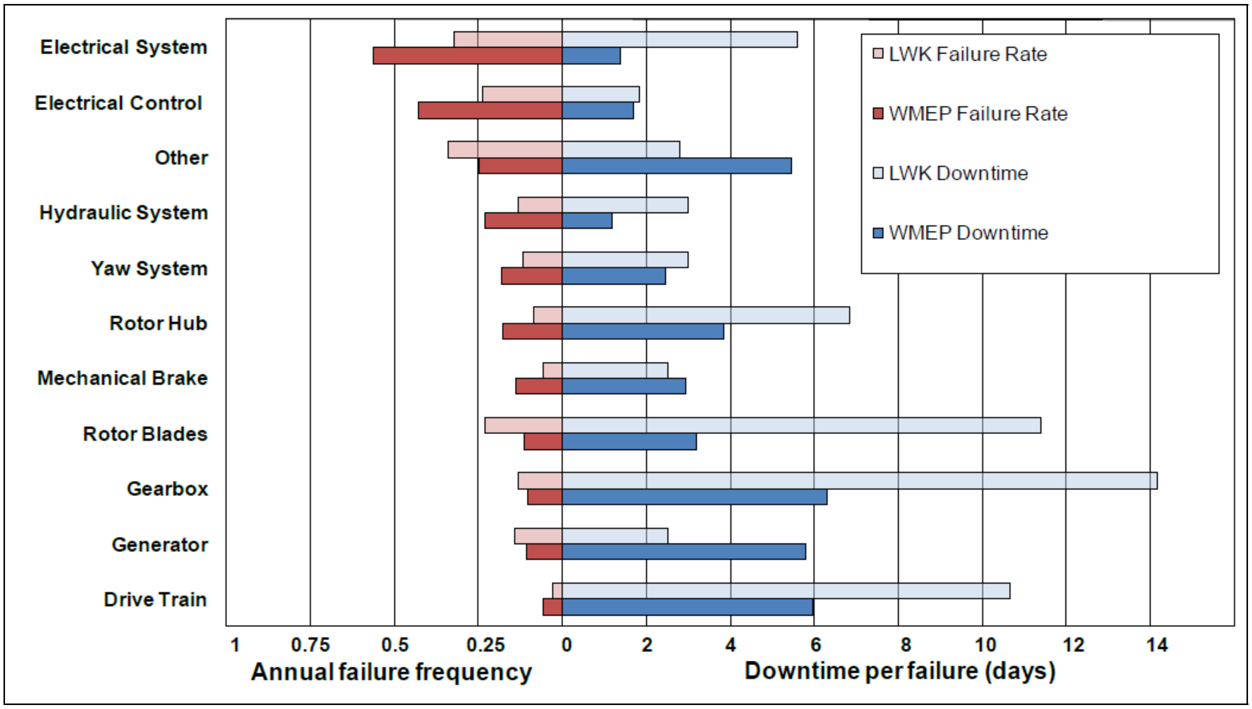

Figure 1-1
Wind Turbine Component Failure Rates and Downtime Statistics [2]

Some potential benefits of implementing SHM on blades include:

- SHM may help mitigate the risk of blade failure through early identification of potential structural problems, providing an opportunity for proactive maintenance.
- Serial defects in blades have resulted in fleet-wide replacements or retrofit campaigns. SHM systems may allow determination of the severity and potential impact of flaws, allowing better definition of the requirements for a retrofit campaign.
- For blades operating with known defects and/or repairs, SHM may reduce the required frequency of physical inspections.
- In-situ sensing of operating conditions and associated blade loads could be used to optimize future blade designs.
- Reliability may increase through the use of real-time loads measurement as input data to the turbine control system.
- Detecting the conditions which cause failure is critical to component reliability. By correlating operating conditions with SHM data, conditions which contribute to structural failure could be detected and potentially avoided.
- Wind projects with turbines using SHM may receive better financing or insurance terms due the perception of lower risk associated with improved reliability. Some European insurers have introduced clauses making certified CM systems mandatory for offshore operation; and others require full roller bearing replacement at certain stages in a turbine's lifetime unless appropriate CM systems are implemented.

- SHM has the potential to reduce O&M costs by automating inspection, reducing turbine downtime.
- SHM has the potential to extend blade life by allowing operation of blades beyond their original design life when they are known to be in good condition.
- SHM may provide an environmental benefit by allowing the extension of useful life of blades, reducing the disposal rate of blades, and improving the knowledge of the structural state of blades during operation, potentially allowing for blades that are constructed with less material.
- Application of SHM is possible on both onshore and offshore wind turbines. Given the more challenging access to offshore turbines for maintenance, SHM has elevated potential for benefit on offshore turbines.

While the application of SHM to blades may reduce downtime, there are costs associated with implementation and operation of an SHM system. The relationship between these costs and benefits is further explored in Chapter 4. Before presenting the cost-benefit analysis, however, it is helpful to describe the construction of a typical blade incorporating an SHM system, potential ways blades can fail, and the architecture of a typical SHM system that can monitor for those failures. We begin with typical blade construction and ways blades can fail.

2
WIND TURBINE BLADE CONSTRUCTION AND FAILURE MODES

This chapter provides context for integration of SHM systems into a modern wind turbine blade by describing the structure of a typical blade, and ways that the blade can fail. This context forms the basis for both operational and design requirements of the SHM system and the cost-benefit analysis of the application of SHM to wind turbine blades.

Structural Elements

The design and application of SHM systems to wind turbine blades is directly affected by the structural elements in the blade. These basic elements determine which areas require monitoring, and what the approach to monitoring will be. In order to provide background for how SHM systems may be applied to MW-scale wind turbine blades, this section presents some current trends in the construction of typical commercial blades. Reporting blade design and construction information reliably is challenging for several reasons. The research and development efforts of each manufacturer are usually kept proprietary until a new product or innovation is ready to be marketed. Also, both the size and manufacturing technologies of MW-scale blades are rapidly evolving. As a result, any attempt at reporting the "status quo" is bound to be at least slightly outdated by the time it is published. Nonetheless, there are consistent trends in the fundamental structural elements of blades across manufacturers. The standard blade described here represents typical modern blade construction.

Figure 2-1 is a section-view illustrating a typical structural architecture representative of current commercial blade designs.

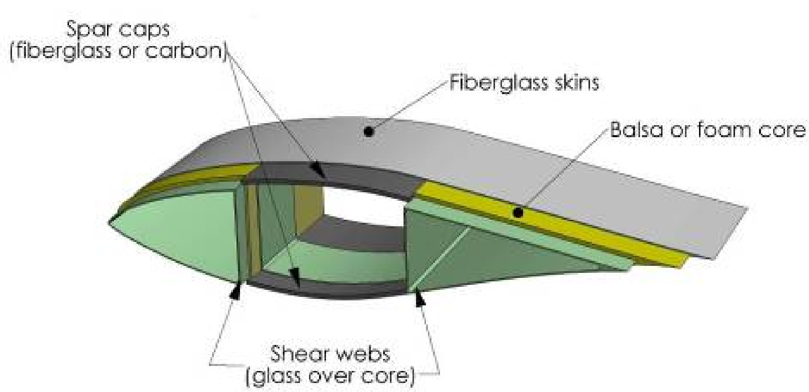

Figure 2-1
A Typical Architecture for Modern Wind Turbine Blades

The primary structural members in a typical modern wind turbine blade are spar caps and shear webs. There may be one or more shear webs that carry shear between the spar caps. Spar caps are designed with relatively thick laminates of primarily unidirectional fibers (oriented in the spanwise direction) to carry flapwise bending loads. The exterior skins and internal shear webs are typically sandwich construction, consisting of biaxial or triaxial fiberglass laminate separated by a low density core material, such as foam or balsa wood.

The types of structural members in a blade will drive the failure modes anticipated for the blades, which will in turn affect the selection of the SHM methods employed for that blade. As an example, the majority of blades include adhesive bonds, but some designs (notably Siemens) do not. For a blade lacking adhesive bonds by design, an SHM system to detect bond line failures would obviously not be needed. When blade designers are laying out the basic structural elements of the blade, SHM system design and selection should be considered as a part of the blade design. This integrated design approach will maximize the benefit obtained by the SHM system.

If a damage-tolerant design approach [3] is accommodated in future blade standards such as International Electrotechnical Commission (IEC) Standard 61400-5, weight savings may be realized through the use of SHM systems. SHM systems have the potential to increase the probability of detection of a critical damage feature, which may enable reduction in the structural requirements for some blade designs. This approach may make the operation of the SHM system critical to the operation of the blade, which may require certification (including testing and validation) of the SHM system prior to commercial operation.

Materials

Materials are an area where broad innovation in wind turbine blade technology is continually occurring. Material selection and application influence the way that blades are manufactured, failure modes, and the behavior of physical phenomena such as acoustic wave transmission, all of which will affect the selection, performance, and behavior of SHM systems. Typical materials employed now in wind turbine blades are briefly described below.

Fiber Reinforced Plastics

Fiber reinforced plastics (FRP) are the most widely used materials in wind turbine blades. FRP consists of a polymer resin reinforced by fibers. Fiberglass is the most commonly used fiber reinforcement in wind turbine blades. Fiberglass fiber reinforced plastics (FFRP) are a good material choice for wind turbine blades because of their good resistance to structural fatigue, relatively high strength, low weight, and reasonable cost. FFRP come in many forms and are employed in blades as a thick laminate structure such as spar caps and as thin laminates as face sheets for sandwich structures.

Carbon Fiber Reinforced Plastics

Carbon fiber reinforced plastic (CFRP) structures are similar to FFRP, except that the reinforcing fibers are carbon rather than fiberglass. Although CFRP structures have decreased in price in recent years, they remain more expensive than FFRP structures. However, selective use of carbon fibers in blades is cost-effective because of the weight savings and high ultimate strength of the fibers. The use of carbon fibers in wind turbine blades is primarily to replace or augment fiberglass in highly loaded components of blades such as spar caps.

Sandwich Materials

Sandwich structure consists of two thin, stiff skins (face sheets) surrounding and attached to a lightweight, relatively thick core. The core is typically lower-stiffness material than the face sheets, but its thickness gives the sandwich structure relatively high bending stiffness for its overall density. In blades, sandwich structures are typically used for shear webs and aerodynamic surfaces such as the blade shells. Typical materials that constitute the sandwich core in blades include balsa wood and foam.

Innovative Materials

As materials science is continually evolving, new material innovations are being employed in wind turbine blades to increase strength and stiffness, enable improved aerodynamics, save weight, reduce cost, and minimize the environmental footprint of blade manufacture, use, and disposal. Integration of SHM systems could also be improved with the use of innovative materials. For example, fiber optics show promise as an SHM sensing system for blades, but these fibers must be embedded in (or applied to) the blade laminate. This increases the complexity of blade manufacture. Blade materials that themselves are the sensing elements of SHM systems would allow employment of an SHM system without increasing manufacturing complexity. As materials innovations are applied to blades, SHM technology for blades must keep pace with the advances in materials in order to continue to provide benefit for new blade designs.

Aerodynamic Devices

Aerodynamic devices may be included in blade design in order to affect airflow around the blade to improve performance. While these devices are not typically load-bearing structures, they influence structural loads, and their presence and operation may need to be accounted for in the design of an SHM system for wind turbine blades.

Aerodynamic devices may be passive or active, where passive devices do not require energy input to operate, and active devices require energy input to operate. Examples of passive aerodynamic devices include leading edge turbulator or “zig-zag” tapes, stall strips, and Gurney flaps. Gurney flaps are installed on the inner portion of a blade at the trailing edge of the high-pressure side to increase lift by increasing the effective camber of the aft part of the airfoil [4]. Vortex generators, shown in Figure 2-2, may be installed on a blade’s low-pressure side, and are intended to delay flow separation, allowing increased lift generation at higher angles of attack. Some blade designs employ droop tips Figure 2-3 to increase power performance and reduce noise [5].

Figure 2-2
Vortex Generators [18]

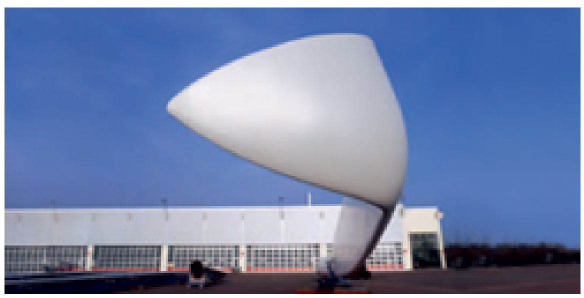

Figure 2-3
Droop Tip

Examples of active aerodynamic devices include surface blowing or suction, surface heating, plasma, or changes in section shape. Shape changing may be actuated by microtabs, ailerons, flaps, or deflection with "smart" materials. Active and passive aerodynamic devices are the topic of current research [6].

Segmented Blades

Wind turbine designs are trending towards larger rotor diameters. As blade dimensions increase, segmented blade designs have appeared as a way to ease transportation requirements [7]. Blade segments can be transported to the site separately, and the complete blade can be assembled on site. Segmented blades require joints, which will affect the installation and behavior of SHM systems. Couplings will be required to allow transmission of SHM data across the joints, and the joints themselves could benefit from some type of SHM.

Manufacturing Methods

Most modern blades are fabricated using a resin infusion process. Figure 2-4 schematically illustrates this process. Dry fabric and laminate materials (reinforcement stack) are placed between a vacuum bag and mould tool, and resin is drawn into and through the dry fabric after vacuum has been applied. The resin cures to form the polymer matrix that supports the fibers of the fabric.

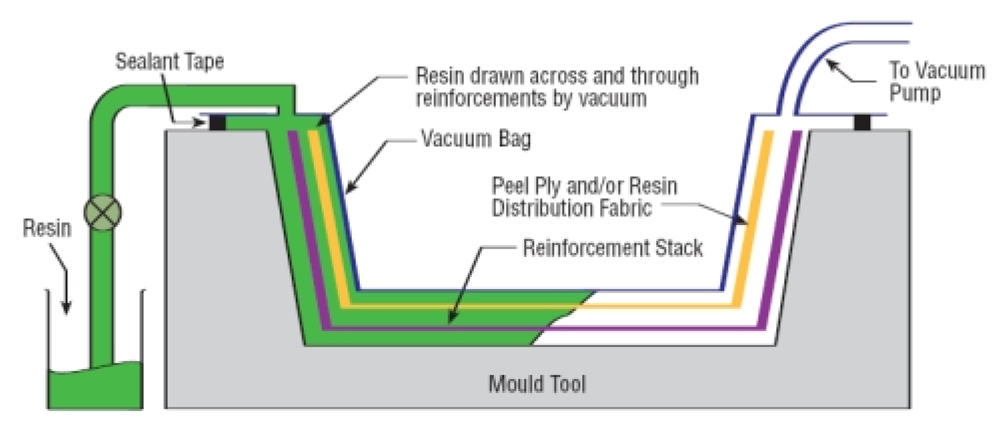

Figure 2-4
Resin Infusion Blade Manufacturing Method [8]

Alternate fabrication methods are also employed, such as the prepreg process, which differs from infusion methods in that all adhesive required to form the finished composite is already present in the supplied pre-impregnated fiber rolls. Prepreg benefits include more controllable resin contents and fiber alignments than the infusion method. Filament winding of reinforcement materials is also performed during fabrication of some blades.

Integration of SHM Systems in Blade Structure

Some SHM systems can be embedded in blades during manufacture. It may be advantageous to install fiber optics, piezoelectric elements (and associated wiring), or other sensing elements directly in the laminate, because the most direct coupling between the structure and the sensing element can be achieved. Embedded sensors are also protected from environmental influences such as moisture or handling damage. Embedding sensing elements in the structure, however, introduces a non-structural inclusion (defect) in the structure, and this must be accounted for in the design of the structure. An additional manufacturing step is required while the blade or blade components are in the mould in order to properly install the sensors. In addition, maintaining embedded sensor systems may require damaging the blade structure in order to access the system. Unless wireless systems are employed, the communication system with the sensor (wiring or fiber optic) must egress from the structure. Careful SHM system design practices are required in order to minimize the possibility of building in either structural problems in the blade due to the presence of the SHM system, or possible points of SHM system failure at the point of wiring or optical fiber egress.

Surface mounting sensing systems is an alternative to embedding sensing systems within the structure. Surface-mounted sensing systems may be installed after the blade has been fabricated, allowing flexibility in production schedules, or as a retrofit to existing blades in operation. Surface mounted sensing systems also allow direct maintenance of the sensing system without damaging the structure. Surface mounted SHM systems, however, are less protected from environmental exposure, and may be damaged during blade handling or by maintenance personnel. Surface mounted systems also carry and elevated risk of failure at the bonding interface.

SHM sensors may have the capacity to monitor the fabrication of the components in which they are installed. For example, if the SHM system includes the capacity to sense temperature, the cure cycle of the blade can be monitored using the SHM system. Residual thermal stresses could be detected. Strains could be monitored while blade components are released from moulds, or during transportation within the factory. These data could be fed back to the blade designers, and could be accounted for in blade design and manufacturing process control.

Furthermore, SHM systems could be employed to monitor for damage during transportation from the blade factory to the wind project location, and monitor for damage when the turbine is being erected. Any damage could be repaired prior to the blade entering commercial service.

After blades have been manufactured and are put in service, SHM systems monitor the condition of the blades. In order to perform this monitoring, the ways that blades fail in service must be understood so that the proper parameters are sensed. The next section discusses potential failure modes of modern blades.

Failure Modes

SHM systems must be designed to detect failure modes relevant to wind turbine blades. As described above, most modern wind turbine blades are manufactured with composite materials; the failure modes of blades are characteristic of failure modes of composite materials. Typical composite structure failure modes are presented in Table A-1 of DNV Standard DNV-OS-J102 [9].

Global Buckling

Global buckling is the failure of a blade panel due to nonlinear increase in deflection resulting from compressive loads beyond the capability of the structure. Buckling might result from either inherent flaws in the original blade design, from manufacturing defects, or from overloading.

Fiber Failure

Fiber failure occurs when the dominant strain parallel to the fiber direction exceeds the tensile or compressive strength capacity of the fiber. Fibers may also buckle, and imperfections can reduce the buckling resistance of fibers. Fibers generally experience brittle fracture due to exceeding the failure strain for the fiber.

Matrix Failure

Matrix failure occurs when the polymer matrix loses stiffness or strength. When the matrix fails, it removes support for the reinforcing fibers, decreasing the strength and stiffness of the laminate. Matrix failure may occur in the case of improper mixing or curing of the resin, so that the matrix strength is below the intended design value.

Inter-Laminar Failure

Inter-laminar failure occurs when the matrix of a laminate fails between adjacent lamina. This failure can lead to separation of the individual lamina, forming a delamination. Inter-laminar failure is generally related to the laminate stacking sequence, and delaminations generally have a greater effect on the compressive strength of a laminate than the tensile strength of a laminate [3].

Sandwich Failure

Sandwich structures have multiple failure modes which are displayed in Figure 2-5; arrows indicate force vectors acting on the structures.

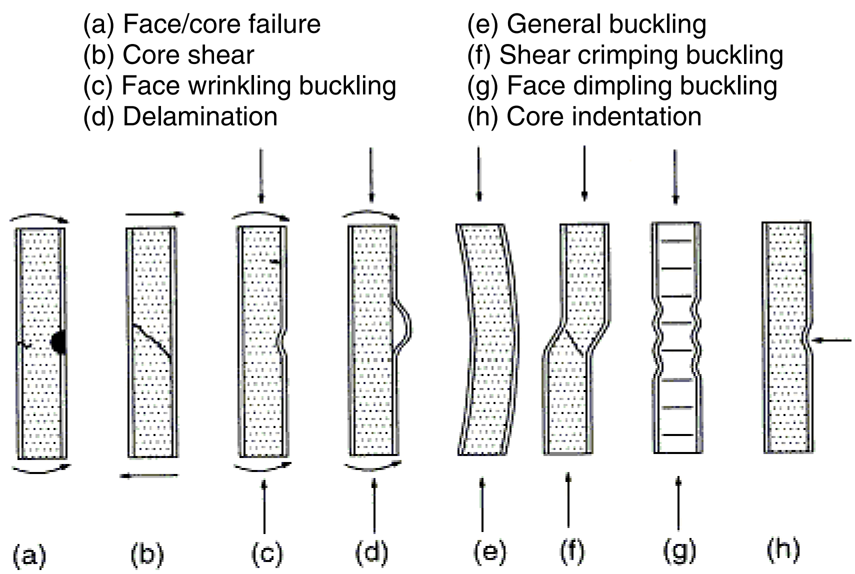

Figure 2-5
Sandwich Structure Failure Modes

The shell panels in wind turbine blades at maximum chord are particularly susceptible to sandwich failure due to the largest unsupported panels being found in this location. Some blade designs feature stiffening beams to avoid general failure, such as (e) shown in Figure 2-5, of large sandwich panels.

Bond Failure

Adhesive or cohesive failure may occur in a bonded joint. An adhesive failure occurs if the failure is between the adhesive material and the adherent. Cohesive failure occurs if the failure is within the adhesive material. Adhesive failure may occur due to poor surface preparation of the bonded components, improper adhesive filling as shown in Figure 2-6 or degradation of the adhesive prior to application. Such voids in adhesive bond may lead to a bond failure. These voids are not visible by visual inspection; SHM systems may be able to detect failures that initiate at such defects.

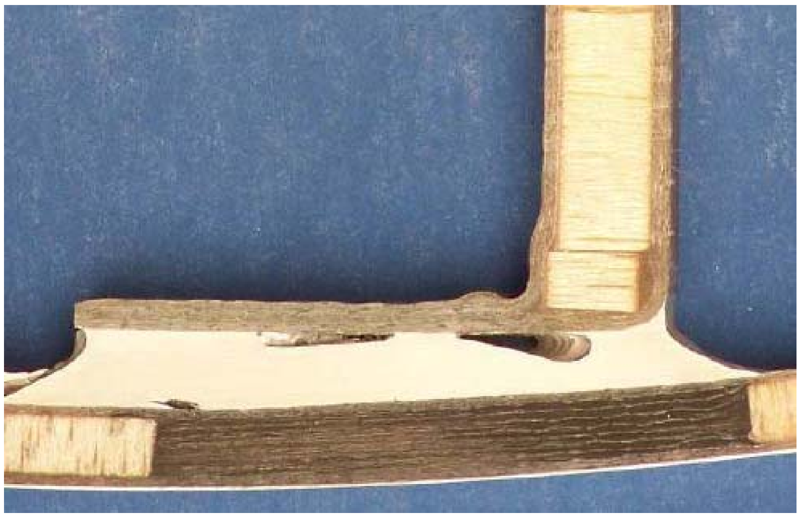

Figure 2-6
Voids in an Adhesive Bond between a Spar Cap and the Flange of a Shear Web [20]

Multiple failure modes may be simultaneously active in a real blade, and an SHM system in a wind turbine blade must account for this. The selection of SHM systems and components must account for the material failure modes and damage types of interest. Industry experience with recent blade failures [10] indicates that the leading contributors to those failures are:

- Manufacturing defects (e.g., wrinkles in laminate, missing or incomplete bond lines, dry fibers)
- Progressive damage starting with: leading-edge erosion, skin cracks, transport/handling damage, lightning strikes
- Excessive loads from turbine system dynamics and/or dynamic interaction with control system
- Out-of-plane forces and distortion of blade sections (“bulging/breathing” effect), mostly in root transition region of the blade
- Excessive loads due to unusually severe atmospheric conditions

With these basic structural elements and failure modes defined, SHM systems that may apply to wind turbine blades can be discussed.

3

SHM ARCHITECTURE, METHODS, AND APPLICATIONS FOR WIND TURBINE BLADES

To maximize usefulness to wind turbine operators and maintainers, SHM systems would ideally detect the presence, type, location, and size of damage in a blade. Numerous SHM systems exist that can meet some or most of these measurement objectives. The most common elements of modern SHM systems are described and summarized here.

Architecture of an SHM System for a Wind Turbine Blade

Broadly, a typical SHM system consists of a sensing system, a method of data acquisition, and a way to interpret the data so that they are usable. Each of these elements, and the unique requirements that these elements must meet in order to function on a wind turbine blade, are discussed below.

Sensors

Sensors are fundamental elements of an SHM system. The capability to automatically interrogate a structure and determine its structural health requires a sensing system. The type of sensors selected for wind turbine blades will depend on the type of damage requiring detection. Failure modes of wind turbine blades are discussed in Chapter 2; the failure modes define the types of damage that a sensing system must detect.

Data Acquisition

Data that are acquired from a blade SHM system can be in different forms depending on the sensor type. Data collection equipment may include components such as signal conditioners, analog-to-digital converters, telemetry, and control computers. Some systems may contain additional components such as digital-to-analog converters and waveform generators. Optical equipment such as demodulators and light sources are required by fiber optic systems.

The rotor of a wind turbine rotates relative to the nacelle. In order for sensed information to be transmitted from a blade to a data system in the stationary frame, a data link that can tolerate rotation must be employed. This may include a wireless link, a rotating optical joint, or a slip ring for a rotating electrical connection.

Wind turbines typically contain multiple electrical systems in a relatively small space. Some of these systems carry high current. The possibility of electromagnetic interference with low amplitude analog SHM sensor signals exists. For SHM systems in blades, interference could be caused by nearby power cables for electric pitch motors. Design features such as proper signal cable routing, cable shielding, and adequate signal to noise ratios can help minimize electromagnetic interference and the effects of electromagnetic interference.

Data Interpretation

Once SHM sensor data are acquired, those data must be translated into information that can enable decisions. The methods for analyzing SHM data are continuously under development, and being applied for operational wind turbine blades [11].

Typically, the presence, type, location, and size of damage are of interest to a user, and the data interpretation system must provide this information to the user. In blades, SHM sensors may also be employed to sense parameters such as loads in the blade, and the presence of ice on the blades. Sensing of loads may be useful for advanced turbine controls, such as cyclic blade pitch.

As a wide variety of SHM systems exist, multiple data interpretation methods are available. Data interpretation system design must account for multiple factors, including:

- Amount of data needed to obtain a high confidence in the results if baselines are required, and if so, how those baselines are established given that blade manufacturing defects are a leading cause of blade failure. If SHM systems are retrofitted to existing blades with a damage history, that history must be accounted for in the baseline.
- Expertise required to interpret the data. Can data be interpreted automatically, by a maintenance technician on site, or is special training (similar to certification for NDI) required?
- Limitations of sensing systems. Accuracy of some sensors, such as optical fibers and piezoelectric sensors, can be compromised by temperature fluctuations in the structure in which they are embedded. This must be considered for turbines equipped with cold weather packages that include heated blades for anti-icing. Methods for the mitigation of these effects are well established and include incorporation of strain-isolated reference gauges.
- Statistical or deterministic approaches.

Current SHM Methods for Wind Turbine Blades

As stated by T. Ashwill at Sandia National Laboratories, “the challenge [of application of SHM to a wind turbine blade] is to use an array of sensors wide enough to monitor the entire structure but yet can detect damage that often initially occurs at small scale, nonspecific locations” [12]. With the basic architecture of sensors, data acquisition, and data interpretation, multiple SHM methods are available that can be applied to wind turbine blades. Selected systems are described below.

Spectral Analysis

Spectral analysis techniques assess damage by comparing a measured frequency response spectrum of a blade with a reference spectrum for the blade in its pristine state. Changes in the frequency response of the structure, assumed to be caused by damage-induced changes in the blade stiffness, can be identified by differences between the referenced and damaged spectra. SHM with spectral analysis is currently offered commercially for blade ice detection and some large-scale damage detection.

Spectral analysis has been proven in gearbox CM, where the target frequencies that indicate specific damage modes are known and analytically derived. For wind turbine blade SHM, the method relies on a knowledge base that is yet to be empirically established for each new blade type and pairing of blade type and turbine [11].

In addition to the difficulty in attributing frequency perturbations to specific types of damage, locating damage by this method has a high degree of uncertainty. One commercially available system reports that the location of trailing edge cracks can be identified within ±3 m while delaminations in the shell can only be identified as either being located in the root- or tip-half of the blade.

Acoustic Techniques

Acoustic Emission (AE) detection is an SHM technique that employs detection of elastic waves in a structure. Waves are generated when failure, such as rupturing fibers or a cracking matrix, occurs. The small displacements that form the waves can be detected by transducers. One method for locating damage is by triangulating the source of the waves when they are detected by multiple sensors.

Results from collaborative research led by Sandia National Laboratories on a TX-100 blade in 2007 found "the diversity of materials in a composite wind turbine blade resulted in challenging acoustic properties for AE NDT. The acoustic velocities were highly anisotropic, and the acoustic energy attenuation was comparatively high resulting in sensor separation of 0.4 meters m or less. This resulted in increased uncertainty in locating the AE events. However, the AE NDT system did detect significant AE events early in the test and therefore was a very informative diagnostic tool during the wind turbine blade test" [11]. Further tests have been conducted by Risø [12]; Risø concluded that while AE is a viable damage detection method, multiple sensor types may be required to detect all necessary information about the damage.

AE is a passive method, in that the transducers detect energy generated by events such as matrix cracking or fiber failure. Other acoustic techniques include active methods, where energy is put in to the structure as a part of damage detection. Piezoelectric transducers are useful for active methods because they convert structural strains to electrical signals, or electrical signals to strains, and can be used to both generate and detect elastic waves in blade structure. Networks of transducers can interrogate the structure, and can detect changes in the acoustic waveforms which may occur due to the presence of damage. This technique is distinguished from acoustic emissions because the targeted acoustic energy is generated by a transducer rather than by structural cracking.

Complex sensor networks may result in high SHM system costs. These networks may require components and features such as high bandwidth signal processing, preamplifiers, and digital signal processors. In addition, manufacturing costs to integrate these networks into the blade structure may be high relative to other sensing systems. In addition to high costs, acoustic sensor systems face challenges in accurately detecting damage due to the anisotropic properties of composite materials. Sensor-based damage detection in composite materials is a topic of ongoing industry research [13].

Optical Fibers

Optical fibers have found multiple applications as SHM sensors. Optical fibers are immune to electromagnetic interference, can be embedded in structures, and can be configured to sense multiple parameters such as strain and temperature. Below are two leading optical-based SHM sensing techniques, applicable for SHM in blades.

Fiber-Optic Bragg Grating

Conventional optical fibers transmit light through a core surrounded by reflective cladding. A Fiber-Optic Bragg grating (FBG) sensor is a modification to the transmitting core of a conventional optical fiber. FBG sensor systems detect changes in strain in a structure. FBG sensors are constructed by modifying a small length, or gage section, of an optical fiber to contain a surface which selectively reflects portions of a broadband light in linear relation to strain at that grating. The center wavelength of the reflected light depends on the period and effective index of refraction in the sensor's gauge section. Any change in period or index of refraction due to mechanical or thermal strain leads to a shift in the center wavelength, which is monitored with a spectral demodulator and translated to strain or temperature.

A variety of demodulation methods are feasible: spectrometers, unbalanced path-length and wave-mixing interferometers, and scanning tunable filters, the choice of which will determine strain sensitivity or resolution and drift from intrinsic temperature sensitivity in the component [15].

FBG systems are particularly applicable to large structures such as blades because multiple sensors may be placed in a single fiber line, which allows for easier integration in large structures during manufacturing. The multiplexing method (wavelength, time, or code division multiplexing) determines the number of discrete sensors on a single fiber.

Optical Fuse

Optical fuses consist of an array of fibers embedded in a blade during manufacturing. Light transmission patterns in the array can be monitored. Broken fibers (in the area of blade damage) cease to transmit light. Patterns in the transmission and non-transmission can be observed to identify the presence and location of damage [16].

New and Cutting Edge SHM Technologies

Some SHM technologies are in the concept development phase, have been applied in other industries, or are undergoing or require further research and development before application to wind turbine blades is feasible.

Modal Analysis

The dynamic characteristics of a structure can be formulated in terms of its modal properties which comprise natural frequencies, mode shapes and damping characteristics. Modal analysis methods are being developed to identify structural damage by observing changes in modal properties. A study performed by the Risø National Laboratory [17] focused on mode shape characteristics as the basis for investigating damage. From that study, plots of the undamaged and damaged mode shapes are shown in Figure 3-1**.** Mode shapes of a blade were described by three functions of the blade radius: flapwise deflection, edgewise deflection, and torsion about the pitch axis, and modal deflections in each of these directions are shown in the figure. Measurements were recorded by piezoelectric accelerometers mounted along the blade's length, and modal analysis was performed using commercially available vibration analysis equipment.

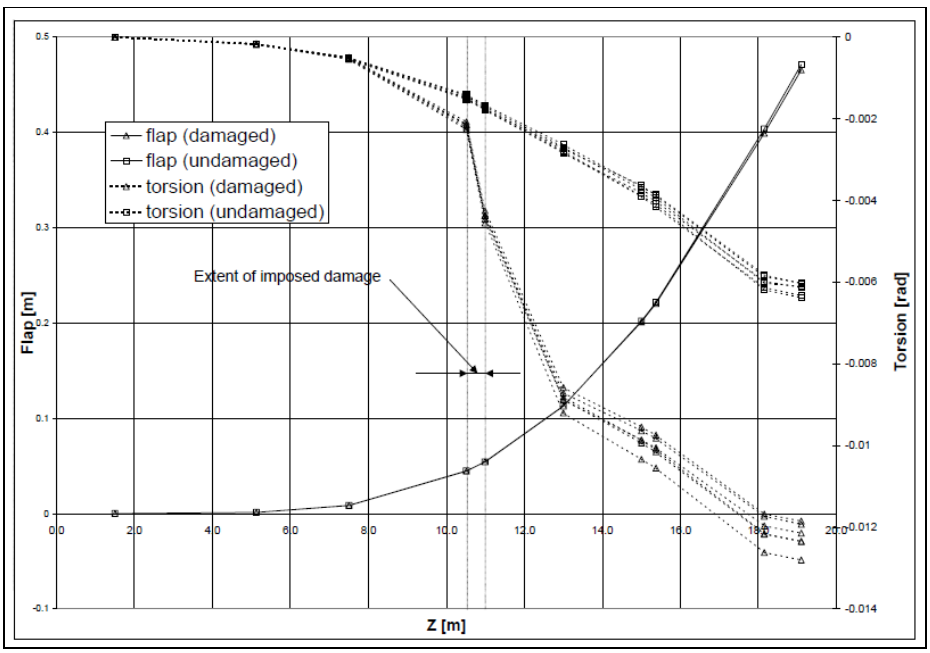

Figure 3-1
Risø 1st Flap Mode Shape in Flap and Torsion Components

Risø reports that natural frequency methods cannot provide damage location and may be subject to significant temperature effects.

Fiber-Optic Methods

Further methods that simplify the addition of sensing capability to conventional optical fibers have been researched and are described below.

Microbend

Microbend transducers were developed for such applications as measuring loads and displacement of bridges in the civil engineering industry. Microbend transducers sense the attenuation of transmitted light due to bends in the fiber caused by strain or temperature changes [18].

Plastic Optical Fiber

Unaltered fiber optics may be able to sense strain and damage, and therefore be applied as SHM sensors. This use of unaltered fiber optics for SHM is called the "plastic optical fiber" (POF) method. This method senses strain because a strain in the fiber results in a proportional reduction in light transmittal through the fiber. In research by Takeda [19], light was transmitted along fiber optics embedded in test specimens, and the power of the transmitted light was measured by a photo detector at the receiving end. Optical transmittance was found to reduce as strain and damage increased.

Other similar SHM sensing techniques, including methods that use flaws in optical fibers as continuous sensing elements, are under development.

Wireless Communication

Wireless communication between sensors and data acquisition systems for SHM is a topic of recent research. Wireless systems have the potential to reduce weight by removing wires, increase reliability by eliminating wire junctions, reduce installation costs, reduce initial SHM system design and fabrication costs, and allow for increased sensor density without increasing wiring complexity. With wireless systems, data can be transmitted from the rotor to the nacelle without slip rings or other rotary junctions.

Low power wireless radios are commercially available and are small enough to be embedded in structures. Some radios, such as radio-frequency identification (RFID) tags, do not require power and can be interrogated remotely. When provided with sensing capability, a RFID-based system has the potential to allow low-cost installation of wireless sensing networks in blades.

For wireless system elements that require power, energy harvesting technologies can be employed to eliminate the need for either powering sensors or providing an energy storage system such as a battery. Ambient mechanical energy (vibration), thermal energy (temperature difference), or electromagnetic energy (light), are all potential sources of energy for powering wireless devices.

Direct Write

Technologies are developing that may allow writing of circuitry directly onto structures such as blades. This technology may allow deposition of sensors directly on to the surface of a blade, reducing the cost of application of large sensor networks to wind turbine blades [20].

Current Applications of SHM in Wind Turbine Blades

Although SHM has been tested in multiple research projects and applied in commercial production of blades, detailed information for commercial applications are not widely disseminated in public sources. Two current applications of SHM in wind turbine blades, selected from publically-available sources, are discussed here.

Sandia Sensor Blade Project

Sandia National Laboratory is currently leading the Sensor Blade project, a multi-partner research project that is building and testing a blade containing multiple suites of SHM sensors [21]. The objective of the sensor blade project is to integrate SHM sensors with a turbine control system to enhance control of the turbine based on structural load data collected in real-time.

Sensor systems installed in the blades include:

- Embedded FBG sensors for sensing strain and temperature to obtain blade shape
- Inner surface-mounted FBG sensors for sensing strain and temperature to obtain blade loads
- Inner surface-mounted accelerometers to obtain blade shape and loads, and to perform SHM
- Metal foil strain gages for sensing strain to obtain loads
- Resistance Temperature Detectors to detect temperature
- Acoustic emission sensors for detecting damage

The instrumented blades have undergone static and fatigue testing, and the results are available in reference [13]. In addition to static and fatigue testing, Sandia is conducting a field test of the Sensor Blade on a turbine at the U.S. Department of Agriculture - Agriculture Research Service in Bushland, Texas. This test turbine is pictured in Figure 3-2. Loads and deflections will be measured during turbine operation, and streaming video will be captured during turbine operation in order to detect the blade shape during operation.

Figure 3-2
Test Turbine for the Sandia Sensor Blade Project in Bushland, Texas [14]

Results of the Sensor Blade project are anticipated to advance understanding of the requirements on SHM systems for wind turbine blades.

Moog/Mitsubishi

Moog is providing a fiber optic-based rotor monitoring system for analysis of the blade condition. The Moog system is currently being applied to blades for Mitsubishi wind turbines [22]. Moog's proprietary Rotor Monitoring System (RMS) is an SHM system based on FBG sensors. Four sensors are located at the root of each blade. These sensors measure real-time strain data that is transmitted to an interrogator unit mounted in the hub. The strain data are analyzed to generate edge and flapwise bending moments. In addition, fundamental and higher order resonant frequencies of the blade are determined, from which the RMS system infers blade condition.

In addition to the assessment of blade condition, the Moog system is intended to detect the presence of ice, rotor imbalance, yaw misalignment, and lightning strikes.

Non Destructive Inspection (NDI)

Both SHM and non-destructive inspection (NDI) or non-destructive testing (NDT) systems seek to assess the condition of a structure such as a wind turbine blade. SHM is distinguished from NDI and NDT in that SHM systems have sensing elements permanently attached to, or integrated into, the blade, whereas NDI/NDT systems are separate from the blades. As SHM systems are a part of the blade structure, SHM systems have slightly different, and potentially increased, functionality over NDI systems, such as adding the capability to collect real-time data on blade loading.

Industry experience has indicated that many blade failures are initiated by undetected manufacturing flaws. To mitigate the risk of structural failure due to manufacturing flaws, NDI is employed during manufacturing to inspect blades, detect flaws, allowing the flaws to be repaired. Visual inspection, tap testing, radiography, ultrasound and thermography are methods and technologies employed by wind turbine blade manufacturers to inspect for flaws. In addition to enabling repairs, flaw data from NDI systems can enable blade manufacturers to continuously improve quality, minimizing the occurrence of flaws.

Once blades are in service, NDI techniques are applied in order to assess the condition of the blade structure. Field application of NDI may be complementary to some SHM applications where the SHM system has defined the general vicinity of an anomaly but does not have the resolution to clearly locate the damage, or describe the damage in detail. Similarly, SHM systems could be retrofit to a blade to monitor a critical region where an inspection with NDI has located a structural anomaly.

Additional NDI technologies that the wind industry has shown interest in include shearography, electronic speckle pattern interferometry, and digital image correlation. These technologies are the subject of ongoing research.

In order for SHM systems to exhibit a positive future return on investment, in wind turbine blades, conditions such as those that may lead to failure must be detected, and operators must be given adequate notice to repair incipient damage. A cost-benefit analysis in Chapter 4 explores the net present value of SHM systems for a range of sizes of offshore and onshore turbines.

4

PROBABILISTIC COST BENEFIT ANALYSIS OF A STRUCTURAL HEALTH MONITORING SYSTEM FOR WIND TURBINE BLADES

In this chapter, we examine the estimated net present value (NPV) of an SHM system applied to wind turbine blades. Cost-benefit analyses on SHM systems in wind turbine blades have been conducted in prior work; however, this study is unique in that probabilistic parameters are included as a part of the analysis.

The following sections explore the NPV of an investment in SHM system for blades in three scenarios:

1. Onshore project with turbine ratings ranging from 1.5 to 3 MW
2. Onshore project with turbine ratings ranging from 3 to 5 MW
3. Offshore project with turbine ratings ranging from 2 to 10 MW

Model Structure

The cost-benefit analysis is driven by a net present value (NPV) model that considers various positive and negative cash flows throughout the life of the project. The NPV for a project with instrumented blades (blades with SHM systems installed) is compared to the NPV for a project with non-instrumented blades at various points in the project life. The sources of cash flow included in the model cover all major costs directly influenced by the inclusion and utilization of an SHM system and are listed in Table 4-1.

Positive cash flows are the saved costs in avoided downtime, avoided replacement costs, and avoided inspection cost. As an example of how positive cash flows are calculated, avoided inspection cost is calculated as follows:

*Avoided inspection cost = Cost of inspections for fleet – cost of inspections per year per turbine * number of turbines in fleet * (1-inspection reduction factor)*

In this example, if the inspection reduction factor is 0.5, inspections are reduced 50% and the savings is a positive cash flow of 50% of inspection costs. If the inspection reduction factor is 0.8, then the inspection costs are reduced to 20% of their original cost and the 80% savings is a positive cash flow for the PV and NPV calculations.

Table 4-1
Sources of Costs, Avoided Costs, and Associated Dependent Factors

Cost	Dependent Factors
Capital cost of blade with or without SHM system	Capital cost of a non-instrumented blade
	Added cost of an SHM system
Cost of blade repairs	Blade failure rate
	Early detection success rate
	Fraction of actionable events (1)
	Cost of repair
Cost of blade replacements	Blade failure rate
	Early detection success rate
	Fraction of actionable events
	Cost of replacement
Cost of inspections	Cost of inspection
	Ability of SHM to provide equivalent inspection information
Cost of loss in electricity sales revenue due to downtime	Blade failure rate
	Early detection success rate
	Fraction of actionable events
	Capacity factor of the wind project
	Electricity sale price
	Downtime associated with each blade failure
	Downtime associated with each blade repair
Avoided Cost	**Dependent Factors**
Capital cost of blade with or without SHM system	Capital cost of a non-instrumented blade
	Added cost of an SHM system
Avoided cost of blade repairs	Blade failure rate
	Early detection success rate
	Fraction of actionable events
	Cost of repair
Avoided cost of blade replacements	Blade failure rate
	Early detection success rate
	Fraction of actionable events
	Cost of replacement (2)
Avoided cost of inspections	Cost of inspection
	Inspection reduction factor
Avoided cost of lost electricity sales revenue due to downtime	Blade failure rate
	Early detection success rate
	Fraction of actionable events
	Capacity factor of the wind project
	Electricity sale price
	Downtime associated with each blade failure
	Downtime associated with each blade repair

1. In the context of this analysis, an actionable event is a problem with a blade, such as a crack in fiberglass laminate that is detected by the SHM system, and maintenance action such as a repair can be taken to correct the problem. Actionable events would include problems detected by an SHM system where the turbine can be shut down, inspections can be performed, repairs can be made, and the turbine can be returned to service.

2. Cost of blade replacement includes the cost of deploying a crane to the site.

The NPV is calculated by first summing all positive and negative costs for each year of operation; second, discounting the annual aggregate net costs to present values at each year using the equation:

$$PV = FV/[(1+i)]^N$$

where N is the period of the cash flow, FV is the net future cash flow value at period N, i is the interest (or discount) rate, which is the rate of return that could be earned on an investment with similar risk, and PV is the present value.

The NPV at year N is the sum of all PVs from year 1 to year N minus the initial investment. The calculated NPV is plotted for all years 1-20 to illustrate how the performance of the investment changes over time. As shown in the results plots below, some applications of SHM systems pay back more quickly than others, and this information can be used to guide decisions regarding research in SHM technology and the application of SHM technology.

The probabilistic model was executed with 1000 Monte Carlo iterations for each of the three scenarios to generate cumulative probability distributions of the net present values. Using 1000 iterations results in less than 1% variation between model executions. After these runs of the model, a sensitivity analysis was performed. In the sensitivity analysis, the NPV values from each model execution were regressed against each of the influencing variables. Regression coefficients were calculated and are shown in the Results section.

Assumptions and Limitations

Multiple assumptions have been made in order to make the analysis tractable. First, the NPV model assumes calculated present values presented in the section above. This type of model is a common method for assessing a potential investment.

We have assumed that a limited number of factors (listed in Table 4-1) affect the NPV of the SHM system. The accuracy of the results is heavily dependent upon the accuracy of the input parameters themselves; input parameter assumptions, and justifications for those assumptions, are addressed in the section below. Although many input parameters are assumed to be probabilistic in nature, they are assumed to have constant probability distributions over time, except for blade failure rates, which were allowed to change over time. In reality, some parameters will change over time, but we do not expect this would significantly change the conclusions of the analysis.

We assume that turbines with higher power ratings have larger rotor diameters, and therefore larger and more expensive blades.

Maintenance of the SHM system itself is not considered in the analysis because there are few data on maintenance costs for such a nascent technology. Therefore the SHM systems were assumed to be 100% reliable and operable for the duration of the blade life. However, many SHM systems are complex and inaccessible or of limited accessibility once installed, so depending on which SHM technology is employed, maintenance costs associated with the SHM system itself may impact the long-term economic viability of the system.

As with any mathematical representation of reality, the model assumptions limit the applicability of the results. As SHM technology is developing, this analysis is limited by the range of SHM technology available today, and at current price points. No assumptions regarding the development and deployment of SHM technology development have been incorporated into the analysis. That is, the SHM technology installed in the blades is considered to be static over the NPV analysis period. In the event that low-cost, high accuracy SHM technology is developed and rapidly deployed, the economics of the investment in such an advanced SHM system would likely improve.

A specific probability distribution is assumed for each input parameter. Other probability distributions could be considered to further refine the NPV projections, such as distributions fitted to actual field data.

The NPV model assumes a discount rate, as opposed to a rate of return. Also, the NPV model does not allow for inclusion of non-monetary costs and benefits of the investment. For example, worker safety may be improved through implementation of an SHM system because of a reduction in required manual inspections.

Input Parameters

The cost-benefit analysis tests the assertion that while the up-front cost of an instrumented blade is higher than a non-instrumented blade, there will be a positive return on this investment due to decreased turbine downtime, reduced manual inspection costs, and reduced or avoided cost of blade repair. In order to guide appropriate selection of the basic input parameters to the analysis, the factors influencing the estimated true cost of operation and ownership of a non-instrumented blade is qualitatively compared to the factors influencing estimated true cost of an instrumented blade. This comparison is shown in Table 4-2. Items in bold in the table are counted in the analysis as positive cash flows. The downtime costs are directly proportional to the lost revenue in electricity sales because the turbine was shut down for maintenance or blade replacement.

From the differences illustrated by this comparison, relevant input parameters are more easily identified.

Input Parameter Description

Guided by the qualitative comparison above, basic input parameters are determined, and these parameters combine to determine calculated input parameters.

In order to capture the range and probability of possible outcomes of the NPV analysis, uncertain input parameters were assigned triangular probability distributions and allowed to vary while the remaining input parameters were considered to be deterministic and were fixed. The triangular probability distribution is characterized by minimum, most likely, and maximum values.

Figure 4-1 is an example of a triangular distribution for capacity factor, with a minimum value of 0.25, a most likely value of 0.32, and a maximum value of 0.40.

Table 4-2
Factors Influencing True Cost of Operation and Ownership of a Non-Instrumented Blade versus an Instrumented Blade

Non-Instrumented Blade	Instrumented Blade	Differences
Capital Cost + Inspection Costs + Blade Replacement Costs + Downtime Costs + Crane Costs	Capital Cost + Inspection Costs **- Avoided Inspection Costs** + Blade Replacement Costs **- Avoided Blade Replacement Costs** + Downtime Costs **- Avoided Downtime Costs** + Crane Costs **- Avoided Crane Costs**	An instrumented blade is more capital intensive than a non-instrumented blade Inspection costs are not completely offset The cost to replace instrumented blades is higher than the cost to replace non-instrumented blades Downtime costs are not completely offset Crane costs are not completely offset

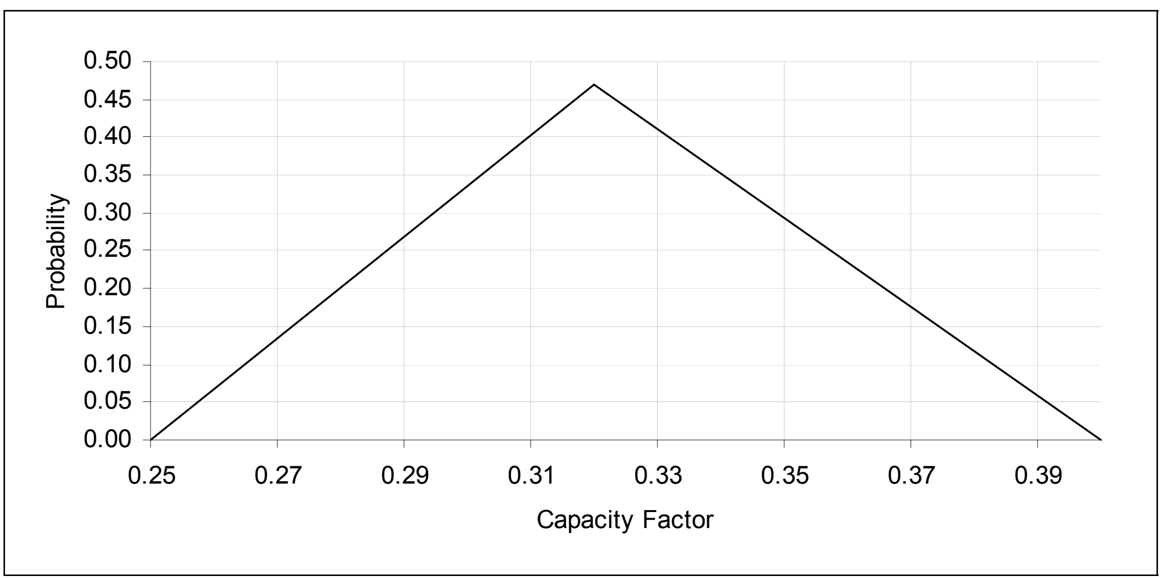

Figure 4-1
Example Probability Distribution for Capacity Factor

The sensor system was assumed to have a probabilistic cost ranging between $5,000 and $10,000 per blade for all three scenarios. The cost was modeled to be independent of blade size because the investment in data analysis systems is assumed to be considerably higher than the addition of new sensors. As a result of the data system cost overshadowing the sensor cost, larger blades with more complex sensor systems may not necessarily be more expensive than instrumented smaller blades.

Blade cost is assumed to be probabilistic, dependent on turbine size, and also dependent on whether the blade is used onshore or offshore. The literature reports a wide range of values for blade costs; some uncertainty is provided in this assumption based on the known cost of a turbine and some estimation of the sub-system itemized costs. Non-instrumented onshore blades are assumed to cost between $60,000 and $150,000, while offshore blades are assumed to cost between $95,000 and $225,000.

The cost of inspections per year (on a per turbine basis) is probabilistic.

The inspection reduction factor with the use of SHM is a fractional input which determines how much the inspections are reduced. SHM systems provide blade health information that may reduce the frequency of required inspections. However, it is not likely that manual inspections could be completely eliminated. Therefore the inspection reduction factor was allowed to vary between 0.25 and 0.80, with 0.50 being the most likely value.

The detection success rate, or the ability for the SHM system to sense a problem that is occurring, is probabilistic. This parameter describes the number of events missed, or false negatives, by the SHM system. No specific SHM system is assumed in this analysis, and this distribution is assumed to cover a variety of SHM technologies. The minimum, most likely, and maximum values were provided with guidance from EPRI and assume mature SHM technology.

Downtime per blade failure per turbine can be impacted by weather delays and site access, and thus may vary significantly for different geographical locations as well as in offshore environments and onshore environments. In this study, a maximum of 336 hours of downtime was assumed for offshore blade failures, and 168 hours for onshore failures. Downtime leads to lost energy production and therefore reduced revenue. The size of the turbine impacts the cost of the downtime because larger turbines would produce more power per hour of operation.

Blade failure statistics per turbine per year and downtime per failure are difficult to obtain, but the work done by Hahn, Guo, Tavner, and others [23, 24] is likely the most comprehensive to date. Their work was used to inform assumptions regarding blade failure statistics. The downtime per blade failure per turbine per year with SHM is assumed to be less than that with the non-instrumented blade in this analysis, because it is assumed that SHM would give advanced warning of a failure such that planning and acquisition of a new blade could be coordinated in advance.

Blade failure data were fit to a “bathtub curve” that is commonly used in reliability predictions; the average failure rate is 0.4 failures per year [22, 23, 24]. This curve is shown in Figure 4-2. The curve generally matches industry experience [25] where blade failure is more frequent in early years, when manufacturing defects tend to lead to failures and also more frequent towards the end of life, when many years of fatigue loading have accumulated. Each point on the bathtub curve is used as a factor to adjust the averaged failure statistics obtained from the literature. When the value of the bathtub curve is one, the full strength of the failure statistics is applied to the NPV analysis. When the bathtub curve has a value less than one, the failure rates are decreased.

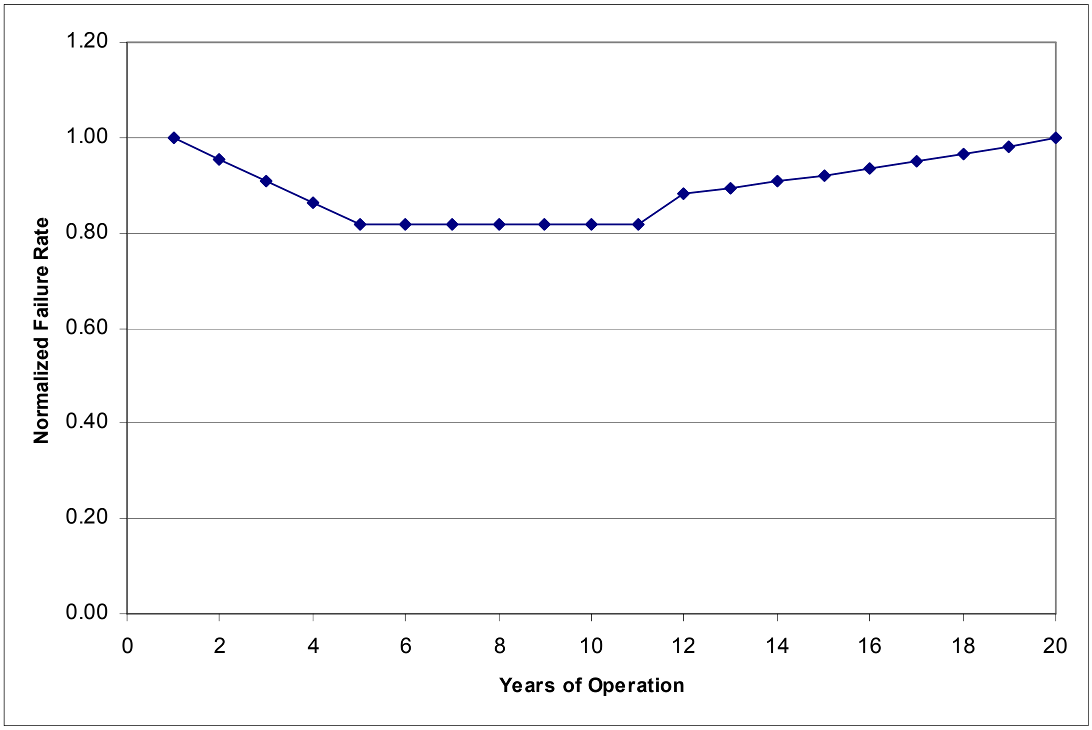

Figure 4-2
Bathtub Curve

Capacity factor is used to calculate loss of revenue due to downtime, and is included as a probabilistic parameter. Revenue per MWh varies on an hourly, daily, and seasonal basis and is included as a probabilistic parameter [24]. As a recent example of offshore revenue, the power purchase agreement for the Cape Wind project has been assumed as representative of the maximum [26].

The cost of prevented failure repairs for an event is a probabilistic input parameter that accounts for expenditures associated with an actionable event, even if total failure was prevented.

Summary of Basic Input Parameters

Table 4-3 and Table 4-4 summarize the basic analysis input parameters. Table 4-3 shows input parameters that differ between the three scenarios analyzed and Table 4-4 shows the input parameters that are common to all three scenarios. The standard deviation and mean values of the triangular distributions are included in the tables.

Table 4-3
Assumed Triangular Probability Distributions that Differ between the Analysis Scenarios

	Onshore 1.5-3 MW				
Parameter	Minimum	Most Likely	Maximum	Std Dev	Mean
Turbine Size (MW)	1.5	2.2	3	0.31	2.23
Capacity Factor	0.25	0.3	0.35	0.02	0.3
Revenue per MWh	$60	$120	$130	$15	$103
Blade cost without SHM	$60,000	$105,000	$150,000	$18,397	$105,000
Downtime per blade failure per turbine (h)	36	100	240	43	125
SHM Downtime per blade failure (h)	0	48	168	35	72
Crane costs per failure	$20,000	$55,000	$88,000	$13,892	$54,333
Cost of inspections per year per turbine	$4,000	$8,000	$12,000	$1,635	$8,000
Blade failure per turbine per year	0.03	0.04	0.05	0.00	0.04
Downtime reduction with early detection	0.5	0.8	1	0.10	0.77
Cost of prevented failure repairs per event	$5,000	$10,000	$20,000	$3,122	$11,667

	Onshore 3-5 MW				
Parameter	Minimum	Most Likely	Maximum	Std Dev	Mean
Turbine Size (MW)	3	4	5	0.41	4.00
Capacity Factor	0.25	0.3	0.35	0.02	0.3
Revenue per MWh	$60	$120	$130	$15	$103
Blade cost without SHM	$100,000	$150,000	$200,000	$20,427	$150,000
Downtime per blade failure per turbine (h)	72	168	288	44	176
SHM Downtime per blade failure (h)	0	48	168	35	72
Crane costs per failure	$30,000	$60,000	$95,000	$13,295	$61,667
Cost of inspections per year per turbine	$8,000	$12,000	$16,000	$1,634	$12,000
Blade failure per turbine per year	0.03	0.04	0.05	0.00	0.04
Downtime reduction with early detection	0.5	0.9	1	0.11	0.80
Cost of prevented failure repairs per event	$5,000	$10,000	$20,000	$3,123	$11,667

	Offshore 2-10 MW				
Parameter	Minimum	Most Likely	Maximum	Std Dev	Mean
Turbine Rating (MW)	2	5	10	1.65	5.67
Capacity Factor	0.3	0.4	0.45	0.03	0.38
Revenue per MWh	$90	$150	$175	$18	$138
Blade cost without SHM	$90,000	$157,000	$225,000	$27,592	$157,333
Downtime per blade failure per turbine (hr)	120	360	480	75	320
SHM Downtime per blade failure (hr)	0	168	336	69	168
Crane costs per failure	$80,000	$120,000	$150,000	$14,357	$116,667
Cost of inspections per year per turbine	$25,000	$38,000	$50,000	$5,110	$37,667
Blade failure per turbine per year	0.036	0.048	0.06	0.00	0.05
Downtime reduction with early detection	0.5	0.9	1	0.11	0.80
Cost of prevented failure repairs per event	$7,500	$15,000	$30,000	$4,682	$17,500

Table 4-4
Assumed Triangular Probability Distributions Common to All Analysis Scenarios

	Minimum	Most Likely	Maximum	Std Dev	Mean
Discount Rate	0.05	0.07	0.1	$0	0.07
Detection Success Rate	0.7	0.85	1	0.06	0.85
Hypothetical Cost of SHM System	$5,000	$7,500	$10,000	$1,022	$7,500
Fraction of actionable faults	0.25	0.5	0.75	0.10	0.50
Inspection reduction with the use of SHM	0.25	0.50	0.80	0.11	0.52

Calculated Input Parameters

The basic input parameters are used to generate calculated input parameters, as follows:

Cost of one instrumented blade = cost of a blade without SHM + the cost of the SHM system
*Cost of SHM system per turbine = cost of the SHM system per blade * 3 blades per turbine*

Analysis Results

The NPV of investment in an SHM system differs for each of the three scenarios analyzed. Summarizing the analysis results, Table 4-5 shows the year at which a positive mean calculated NPV is attained for each scenario.

Table 4-5
Calculated Mean NPV of SHM Systems for Three Scenarios

Scenario	Year when mean positive NPV is achieved
Onshore, 1.5- to 3-MW turbines	4
Onshore, 3- to 5-MW turbines	3
Offshore, 2- to 10-MW turbines	<1

Most factors influencing NPV are more favorable for the offshore scenario. For offshore operations, blade replacement costs are higher, costs of inspections are higher, downtime associated with replacement is higher, and avoided cost due to downtime is higher because capacity factors are higher.

Detailed analysis results are provided below. Probabilistic NPV projections, sensitivity analyses, and cumulative probability distributions are presented for each of the three scenarios analyzed.

Onshore 1.5- to 3.0-MW Turbine Scenario

Figure 4-3 shows the results of the NPV analysis for the onshore 1.5- to 3.0-MW turbine. The NPV ranges from the 5th percentile near $20,000 to the 95th percentile near $72,000. The mean NPV of the SHM investment is calculated to be positive after four years of operation. There is little to no probability that the NPV would become positive earlier than year two. The 5th percentile NPV becomes positive after year 8.

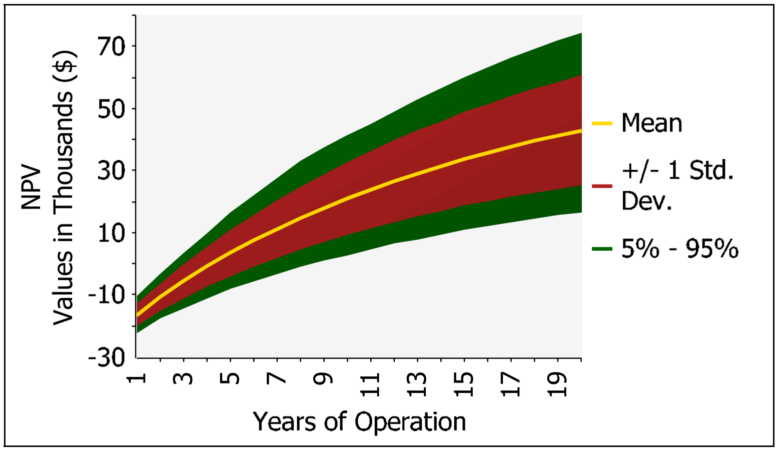

Figure 4-3
NPV Projection for the Onshore Scenario, 1.5- to 3-MW Turbines

Figure 4-4 shows the cumulative probability distribution of the NPV for the 1.5- to 3.0-MW turbine scenario at year 20. The figure indicates the probability that the NPV in year 20 is equal to a specified value. For example, the NPV at 90% probability in Figure 4-4 is $71,700.

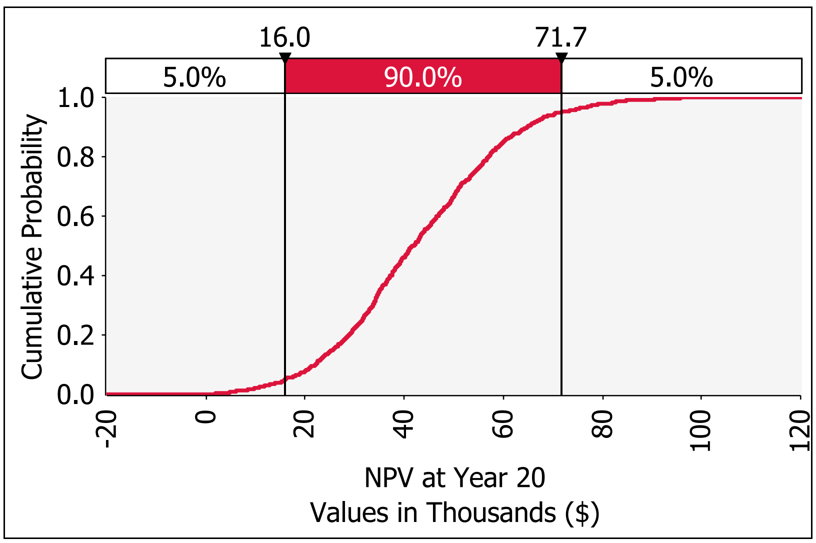

Figure 4-4
Cumulative Probability Distribution for the NPV of a SHM system at Year 20 for the Onshore 1.5- to 3-MW Turbine Scenario

Regression analysis is a way of observing how analysis results change when input parameters are varied. It is useful to see how the NPV of the SHM system changes when, for example, the capital cost of the SHM system is varied.

A regression coefficient is a measure of the relative influence each input parameter has on NPV. A negative regression coefficient corresponds to a negative influence on NPV, and a positive coefficient corresponds to a positive influence on NPV. Regression coefficients indicate the sensitivity of NPV to the input parameters.

Visualizing regression coefficients in a chart is useful because the chart allows easy identification of the relative influence of the input parameters on NPV. The regression coefficients are plotted as horizontal bars, sorted in order of lengths of the bars from top to bottom. This yields what is called a "tornado chart," because it looks like a tornado. Figure 4-5 presents the regression coefficients that exceed 0.1 for this scenario in tornado chart format.

For the tornado charts in this report, a coefficient value of zero indicates that there is no relationship between the input parameter and NPV. A value of +1 or -1 indicates a +1 or -1 standard deviation change in the NPV for a change of one standard deviation in the input parameter.

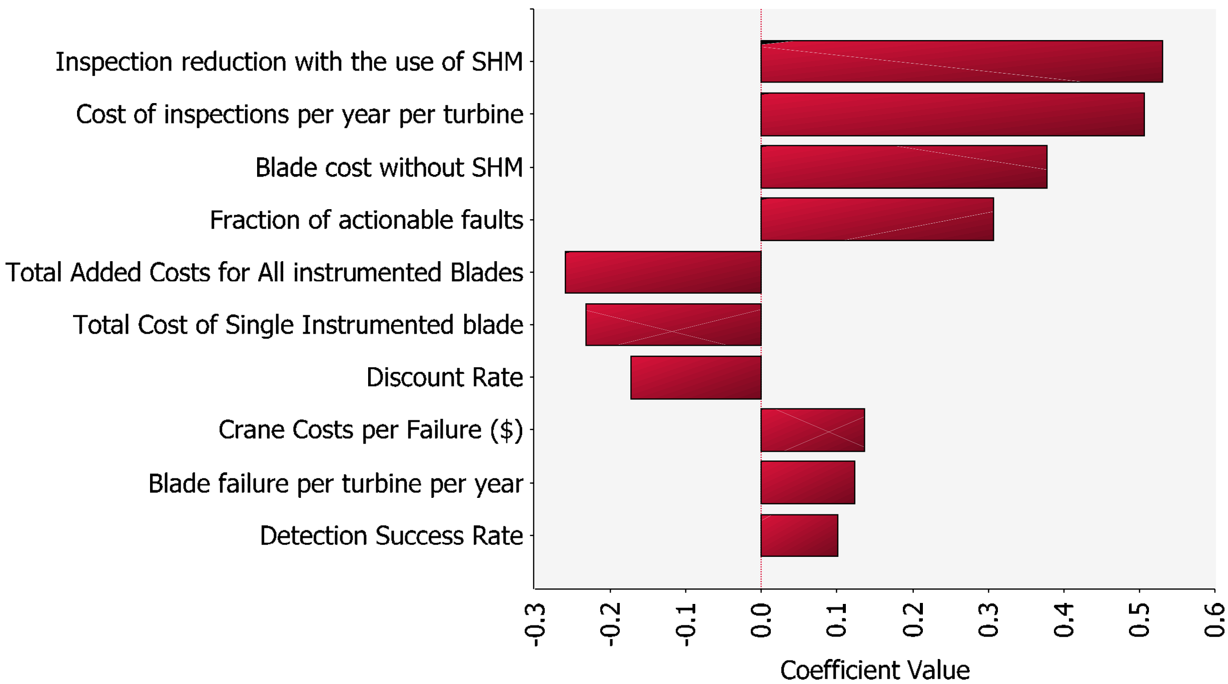

Figure 4-5
Tornado Chart for the Onshore Scenario, 1.5- to 3-MW Turbines

From this tornado chart, several parameters drive down the NPV of the investment in SHM for this scenario as they rise. The added cost of the instrumented blades is the primary negative factor, followed by the cost of an instrumented blade and the discount rate.

The parameters that most positively drive the NPV of the investment in SHM for this scenario are inspection reduction with the use of SHM and cost of inspections per year per turbine (included in avoided costs with the use of SHM).

Onshore 3- to 5-MW Turbine Scenario

A scenario including onshore turbines ranging from 3 MW to 5 MW was also analyzed. In this scenario. The larger turbines have greater energy generation capacity and are therefore more energy generation is lost during downtime. The NPV projection, shown in Figure 4-6, is slightly improved for this scenario, and the importance of the inspection reduction and the cost of inspections per year is more significant, as shown in Figure 4-8. The mean NPV becomes positive by year 3. The detection success rate is a mildly significant factor, as it was in the previous scenario. The cost of the blades and the discount rate are still the primary negative drivers of NPV of the investment in SHM, and the regression coefficients for these negative drivers are now approximately equal, whereas the added cost of the blades was a stronger driver in the 1.5-3 MW scenario. Crane costs are less of a driver in this scenario than in the 1.5-3 MW scenario.

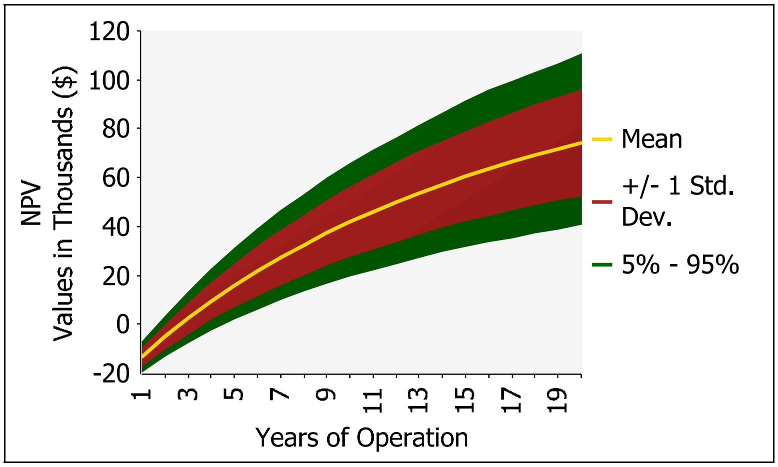

Figure 4-6
NPV Projection for the Onshore Scenario, 3- to 5-MW Turbines

The cumulative probability of the NPV at year 20 for this scenario is shown in Figure 4-7.

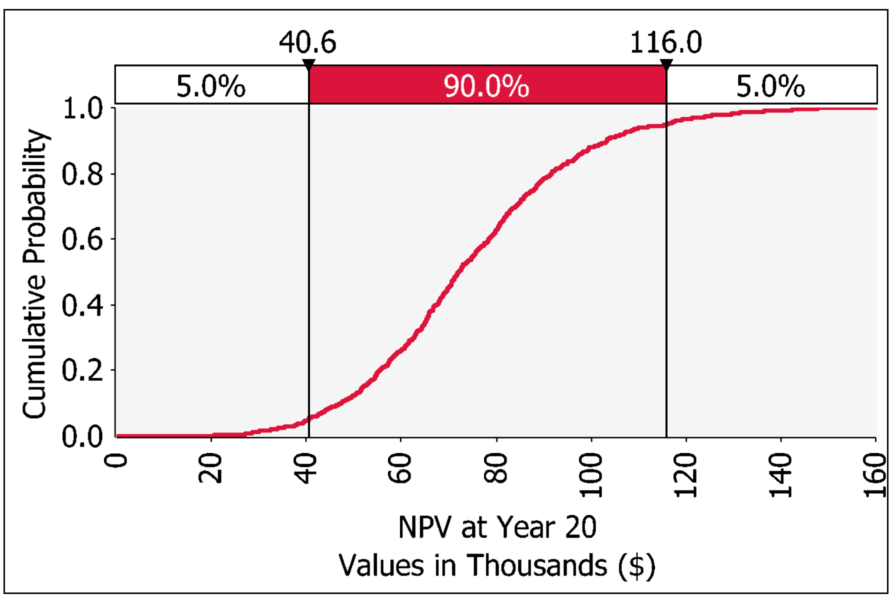

Figure 4-7
Cumulative Probability Distribution for the NPV of a SHM system at Year 20 for the Onshore Scenario, 3- to 5-MW Turbines

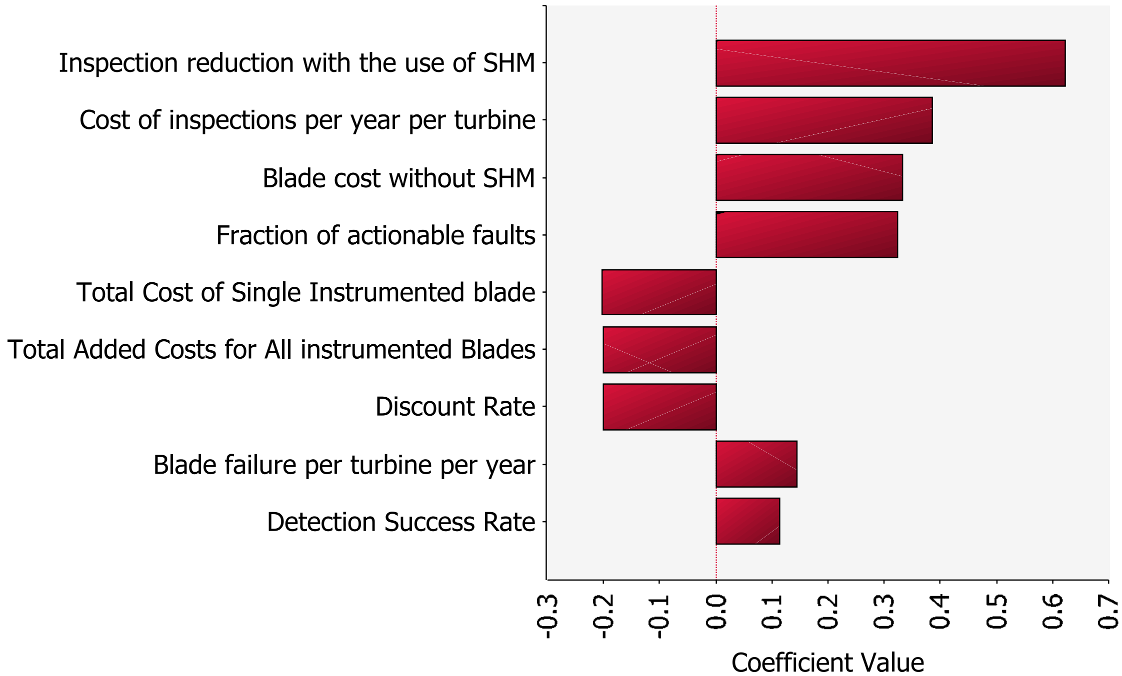

Figure 4-8
Tornado Chart for the Onshore Scenario, 3- to 5-MW Turbines

Offshore 2 to 10 MW Turbine Scenario

For the offshore scenario, at year 20, the NPV ranges from the 5th percentile value, \$150,000, to the 95th percentile value of over \$350,000. The analysis indicates that mean NPV becomes positive almost immediately. When compared to the onshore scenarios, the lower time to positive NPV for this scenario results from the inspection costs. This is shown in the results of the regression analysis (Figure 4-11).

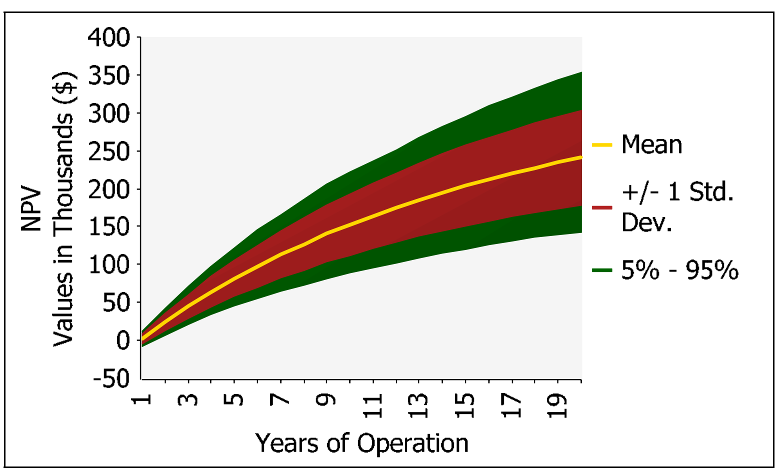

Figure 4-9
NPV Projection for the Offshore Scenario, 2.0- to 10-MW Turbines

The cumulative probability distribution of the NPV for this scenario at year 20 (Figure 4-10) illustrates the probabilities of possible values for NPV.

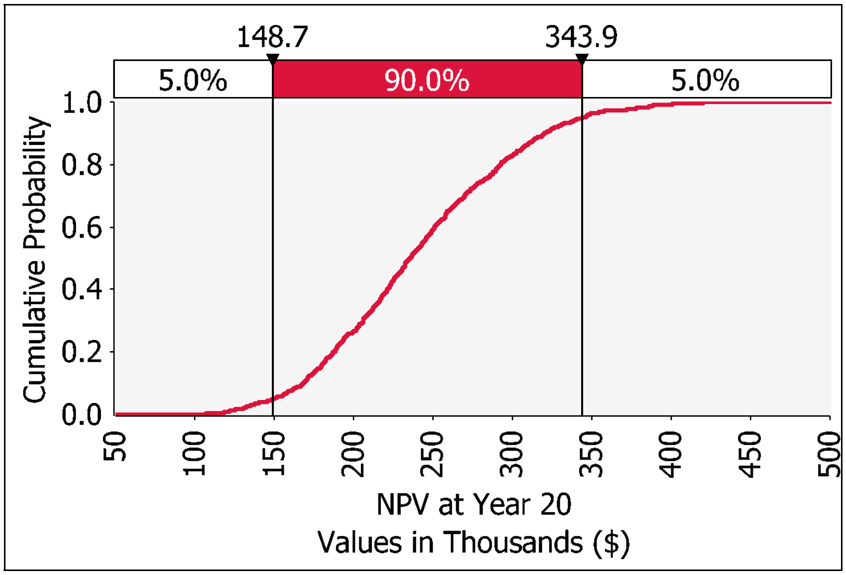

Figure 4-10
Cumulative Probability Distribution for the NPV of a SHM system at Year 20 for the Offshore Scenario, 2- to 10-MW Turbines

Figure 4-11 shows the results of the regression analysis. As with the previous scenario, the results shown include only parameters with regression coefficients that exceed 0.1.

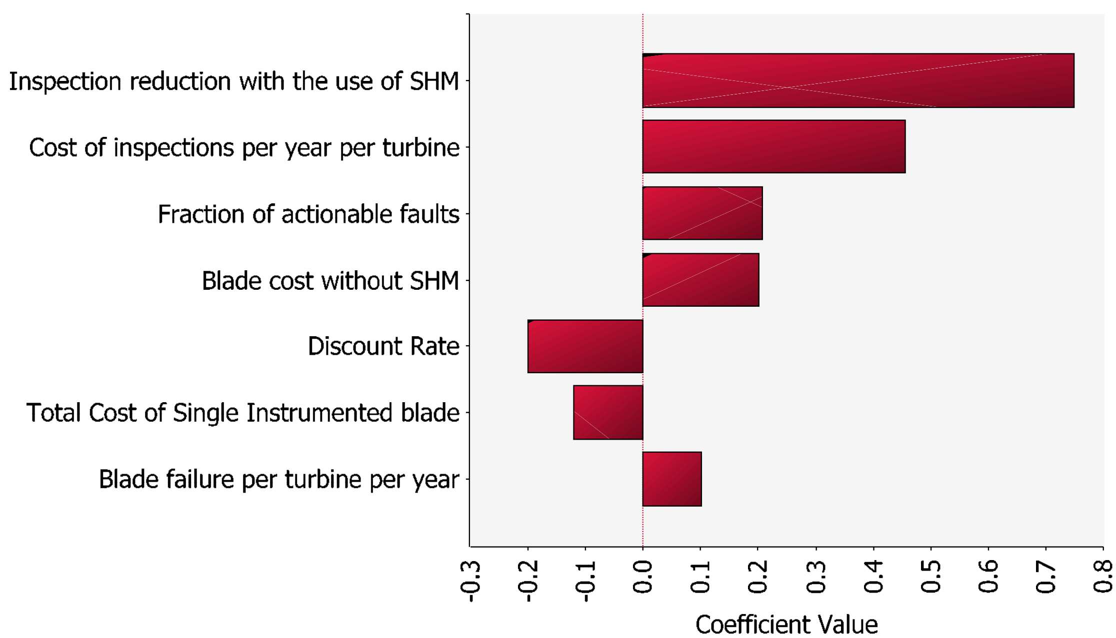

Figure 4-11
Tornado Chart Results for the Offshore Scenario, 2.0- to 10-MW Turbines

The primary positive drivers for the NPV in this scenario are the reduced number of inspections and the cost of inspections per year per turbine. The fraction of actionable faults and the blade cost without SHM are also positive drivers. The sensitivity analysis for the simple payback is similar, but it is more negatively driven by the initial cost and the discount rate does not appear in the calculation.

Summary of the Cost-Benefit Analysis

If the assumptions in this analysis are accurate, SHM systems are likely to have economic viability for wind turbine blades over a 20-year turbine life in multiple application scenarios. The benefit is likely to be most greatly realized in offshore projects where maintenance, inspections, and operation costs are considerably higher, and the turbines are larger. Onshore projects are less tolerant to the added costs of blade SHM systems than offshore projects, as indicated by Figure 4-12, as the onshore cost curves rise sharply with increasing SHM system costs.

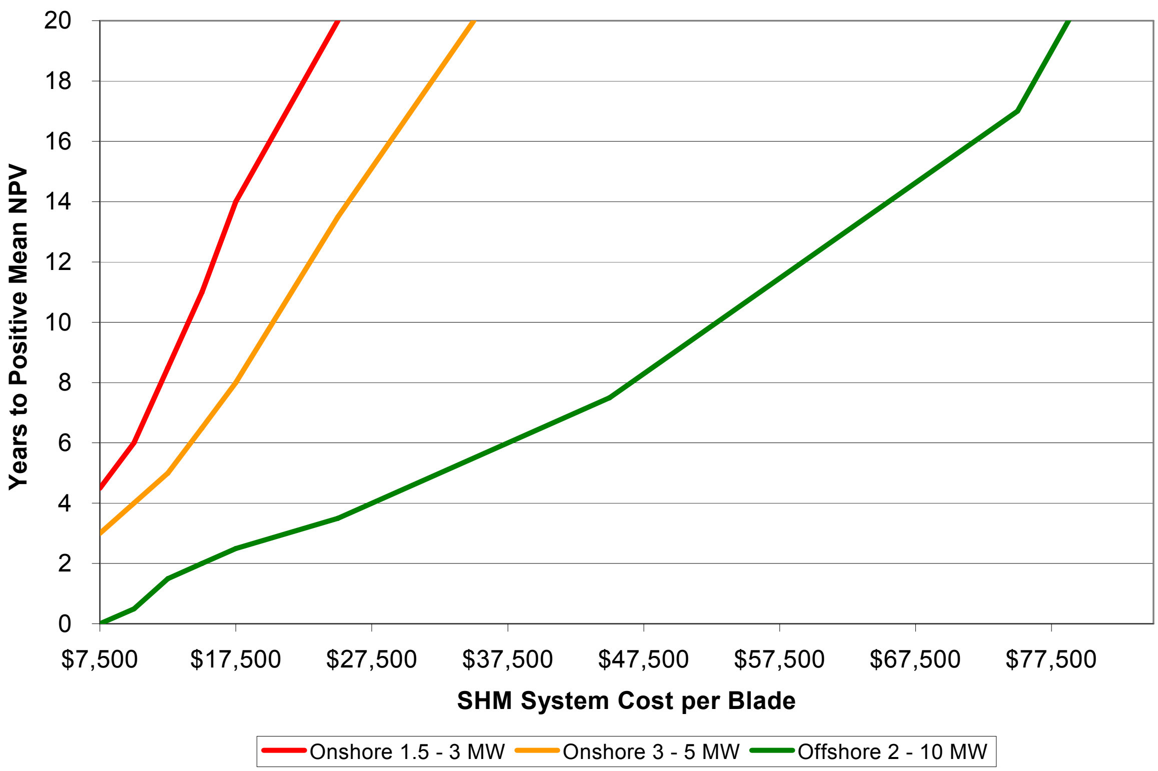

Figure 4-12
Years to Positive Mean NPV as a Function of SHM System Cost

The regression analysis for all three scenarios considered indicates that inspection reduction and inspection costs are key factors in the evaluation of the SHM system viability. A factor that may become a metric for SHM viability for wind turbine blades is the ratio of annual inspection costs to the capital blade cost, which can be expressed as a percentage. In this model, the average inspection cost to blade cost ratio was 7.4%, 8%, and 24.7%, for onshore 1.5- to 3-MW, onshore

3- to 5-MW, and offshore 2- to 10-MW scenarios, respectively. From this, we conclude that special care must be given to the evaluation of inspection costs in order to estimate the viability of SHM systems.

The capital cost of the instrumented blade is one primary negative driver of NPV for the investment in SHM. The configurations of the SHM sensor system selected for a blade will affect its cost. Single-sensor or simple fiber optic systems are likely to show a positive NPV sooner than a complex sensor network that requires considerable data analysis and processing power. The assumed price of $5,000-$10,000 per blade for the SHM system may be more likely for a relatively simple fiber optic system than a more complex distributed acoustic sensor system.

While capital cost was a common negative driver for all cases investigated, it was not necessarily the most significant driver overall. For the onshore scenarios, the avoided inspection cost was most important. This implies that for SHM systems to be successful onshore, they need to be low-cost and provide much of the same information that a manual inspection provides. This also implies that SHM systems will be more beneficial at sites that have high manual inspection costs. High manual inspection costs may result from multiple reasons, including complexity of the blade design, accessibility to inspect the blade, regional weather, availability of appropriate of NDI equipment, and level of skill and experience of inspection technicians.

The discount rate is another negative driver in all of the scenarios, but it is somewhat independent of the SHM technology as it is a financial parameter and set by the entity investing in the system based on market factors and the company’s risk appetite and financial objectives. Nevertheless, the discount rate is a factor negatively driving NPV of investment in an SHM system, and the investment is more attractive at lower discount rates.

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CONCLUSION

While SHM systems are not currently widely deployed on wind turbine blades, the potential exists for SHM systems to have a positive economic benefit for blades. A low-cost SHM system is likely to have economic viability for wind turbine blades over a 20-year turbine life. The benefit is likely to be most greatly realized in offshore projects where maintenance, inspections, and operation costs are considerably higher and the turbines are larger. Onshore projects are less tolerant to the added costs of blade SHM systems than offshore projects.

Multiple SHM techniques are available, and the suitable mix of technologies to meet the requirements for damage detection on blades is yet to be determined. Areas of further research in the application of SHM to wind turbine blades include:

- Maturation and deployment of low cost sensors, sensor networks, and data acquisition systems. In order for SHM systems to be commercially successful, system costs must be minimized.
- Development of expert systems for identification of damage based on sensor data. The field of SHM data interpretation is rich with opportunity for improvement, and application of data interpretation to wind turbine blades is in need of considerable development. Minimizing false positives and false negatives is important to the successful application of SHM systems to wind turbine blades.
- Research in interaction between sensor output and turbine controllers for real-time load control. SHM sensors may be able to perform multiple roles, including providing input for turbine control.
- Creating a path for feedback from SHM systems to blade designers and manufacturers. As data are gathered from SHM systems, designers and manufacturers may have the opportunity to improve designs and manufacturing techniques based on the SHM data.
- Integration of SHM systems for wind turbine blades in standards such as IEC 61400-5. Standards-writing bodies must be aware of the capabilities and limitations of SHM systems so that certification agents can consider the impact of application of SHM systems to blades.
- Generation of more detailed cost-benefit analyses with improved empirical input values. As turbines age and more cost data become available, these data will lead to improved assessment of the costs and benefits of SHM systems applied to blades.
- Research regarding retrofit of SHM systems to operating turbines. SHM systems could be installed on aging blades to mitigate risks associated with fatigue damage late in blade life. In addition, considerable interest in operating turbines beyond their design life exists. SHM could provide operational information to inform decisions regarding continued operation beyond the design life of the turbine.

6
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