DOE

MARKET RESEARCH STUDY

DIGITAL TWINS FOR WIND TURBINES

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1.0 Introduction

The growing importance of the offshore wind industrydrives the current focus on offshore wind turbine (OWT) monitoring, maintenance, and health forecasting. Planned installed capacity is increasing and its geographic reach expanding. To illustrate, at the end of 2020 there was 35.3 GW of installed capacity. Compare this to the projected 270 GW to be installed by 2030. When considering this growth rate over the span of a single decade, this brings with it challenges that are different from the past. The more recently installed OWTs and those installed in the coming decade “are of such size (per turbine) that efforts to efficiently manage lifetime are very attractive to farm operators.”[1] Within this context, digital twin technology has great appeal.

However, this does not come without concerns, including the high costs associated with integrating digital twin technology into wind farms, the extreme computational power that is necessary, data rights (sharing) and from that data sharing – potential liability issues. One concern that comes into play after a digital twin has been provided the necessary data to monitor and maintain asset health – is how to change the model when changes are made to equipment, asset configuration, and state of operation. When changes are made to the physical system, this will require changes to the digital twin and the associated algorithms. “The risk of errors may escalate with the increasing levels of complexity, as the simulation of certain scenarios, such as the addition of new parts at the machine level or operational level changes, may not be precise.”[2] Further, as of February 2023 reporting by the Government Accountability Office (GAO), regulations and standards are not yet fully developed to address digital twin implementation, particularly within scenarios involving more complex application areas. The GAO view is that “users rely on a patchwork of standards for data management, security, and networking established by organizations such as the National Institute of Standards and Technology and the International Organization for Standardization.”[3] This does not preclude the fact that other regulations and standards are available. A global listing of these standards and regulations are listed later in this report.

2.0 Wind Overview

When looking at the state of the wind market, onshore and offshore are typically addressed individually. According to the Global World Energy Council (GWEC) onshore wind will likely pass annual installations of 100 GW by 2024. In contrast, it is forecast that offshore wind will likely install 25 GW+ over the course of a single year – for its first time ever – in 2025. After this offshore marker of 25GW+ annually is reached, the expectation is that installations will accelerate rapidly. GWEC forecasts that 680 GW of wind capacity will be installed globally by 2027; of this, offshore will account for 130 GW and onshore will represent the majority share of 550 GW. Last year, in 2022, only 77.6 GW of additional wind capacity was installed globally. While this was a decrease of 17% as compared to 2021, this still ranked as "the third highest year in history for additions." When looking at offshore wind additions, for 2022 it was 8.8 GW. Here again, while less than half the 21 GW reported for 2021, this was "the second highest volume ever."[4] In the United States, fixed wind turbines are forecast to dominate on the east coast, while floating versions will be concentrated in California and Hawaii.[5]

3.0 Offshore Wind

When speaking to the resource potential for offshore wind installations, approximately 80% of global offshore wind resource potential is found in deep waters (>60 m). This is too deep for fixed-bottom offshore wind turbines. Water at this depth requires floating wind turbines in order to efficiently harness deep water wind. While floating wind contributes only 0.1% of the cumulative offshore wind capacity at this time, the market is still in its early stages with approximately forty floating platform designs and fewer projects of less than 100.0 MW under development. Analysts predict that global floating wind installations will increase rapidly in the coming years due to the development of many 100.0 MW to 500.0 MW projects. Main growth markets that are called out in the literature include France, the UK, the United States, South Korea, Ireland, Japan, Norway, Colombia, and Italy. Looking forward, floating wind turbines are expected to account for 1.8% of the total installed offshore wind capacity in 2030. Factors influencing market growth include countering supply chain issues (i.e., improving the supply chain such that it can fulfill proposed project demand) and securing substantial financial investment and support to develop or modernize both port infrastructures as needed as well as manufacturing facilities.[6]

The following figure details the installed floating wind capacity forecasted for the 2022-2030 time frame.

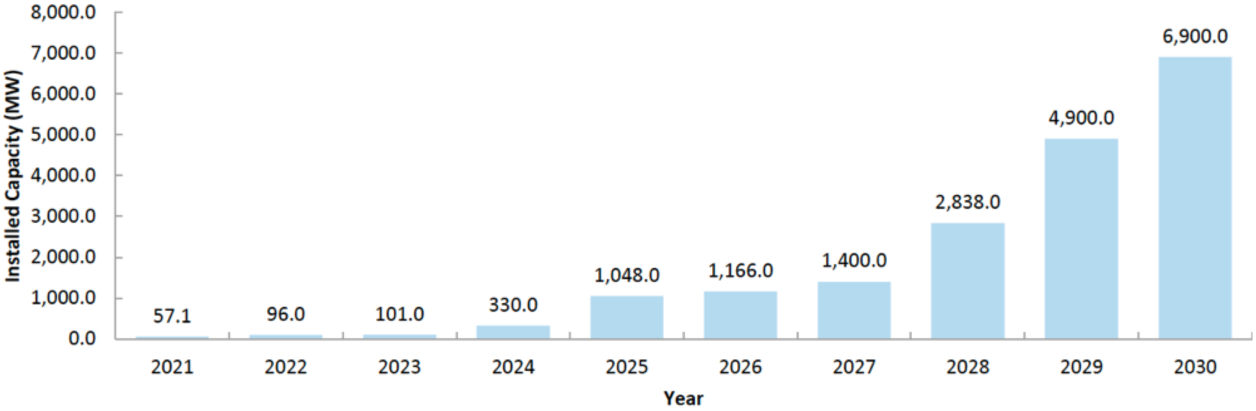


Figure 1: Global Offshore Wind: Cumulative Installed Floating Wind Capacity Forecast, 2022–2030

Source: Reprinted with permission from Frost & Sullivan[7]

Currently, there are three types of floating foundations for floating offshore wind turbines. These include the following:

- **Spar:** A Spar floating foundation is constructed of concrete, steel, or a hybrid combination. The Spar floating foundation is a cylinder that floats vertically in the water.

- **Tension Leg Platform (TLP):** A TLP floating foundation is constructed of steel and consists of multiple columns and pontoons. The TLP's mooring system requires vertical-tensioned tendons that offer stability to this type of structure.

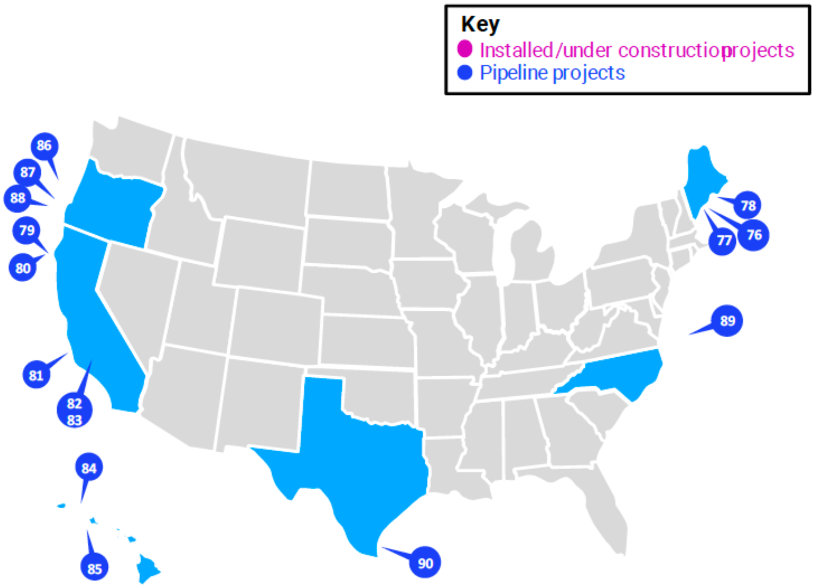
- **Semi-submersible:** A semi-submersible floating foundation is constructed of either concrete, steel, or a hybrid combination. This type of floating foundation consists of multiple pontoons and columns and a hull that is submerged.

The following figure illustrates these three types of floating foundations.

Figure 2: Illustration of Floating Foundation Types (NREL 2022)
Key, Left to Right: Spar, Semi-Submersible, TLP
Source: U.S. Department of the Interior, Bureau of Ocean Energy Management (BOEM), January 2023[8]

3.1 United States Market: Floating Offshore Wind

As of July 2022 reporting, although the U.S. has yet to deploy any demonstration projects, the forecast for floating offshore wind to be deployed by 2030 remains high. In 2021 the target was set for 30 GW offshore wind by 2030. There is an increasing focus on floating offshore wind in the U.S., with most of the interest coming from the west coast – as seen in the figure below. California and Oregon both have set targets of 3 GW floating offshore wind by 2030. Additional states such as North Carolina and Maine, while they have set off-shore wind (OSW) targets, there is "nothing specific to floating wind."[9]



Project	MW
Maine	
76. Aqua Ventus	12
77. Maine Research Array	144
78. Future Floating *	450 - 1500
California	
79. Redwood	150
80. Humboldt WEA *	1600
81. Morro Bay *	700-1000
82. Lompoc/CADEMO	60
83. Castle Wind *	1000
Hawaii	
84. Oahu Northwest *	400
85. Oahu South *	400
Oregon	
86. Coos Bay *	10,000
87. Bandon *	2,800
88. Brookings *	3,400
North Carolina	
89. Central Atlantic E *	1000
Texas	
90. Gulf of Mexico *	2000

** = call areas*

Figure 3: Map of American Floating Offshore Wind Deployment

Source: 4COffshore; Carbon Trust, July 2022[10]

It is assumed that given the offshore environment, as well as the size and complexity of the offshore wind turbines, that digital twin technology is likely to be implemented with offshore wind. In the following section, digital twins and their application with larger and more complex turbines will be introduced.

4.0 Digital Twins

Having first been adopted by NASA,[11] today digital twin (DT) technology is used in numerous industries. A digital twin is a virtual (digital) representation of a physical object, created to provide insight into the performance of the physical object it represents. DT technology can be used across the entire manufacturing proess from the design phase to monitoring the performance of the manufactured item and maintenance planning.[12] Of interest when applied to wind turbine technology is the ability to use digital twin technology to aggregate all the data about the object or asset (both historical and real time) and use it to monitor, analyze and predict future behavior of the component, process and/or system.

According to Amazon Web Services, “Digital twins are widely used in the energy sector to support strategic project planning and optimize the performance and lifecycles of existing assets, such as *offshore installations*, refining facilities, *wind farms*, and solar projects.”[13] To accomplish this goal a digital twin collates information from various sensors and sources installed within assets after which the DT performs high-level data cleaning and aggregation by employing big data technologies. When data are converted to a structured form, then the DT performs high-level data analysis, using artificial intelligence (AI) to draw conclusions and form decisions to move forward with. As the digital twin learns from historical data, in tandem the DT’s intelligence grows with increasing data fed into the system.[14]

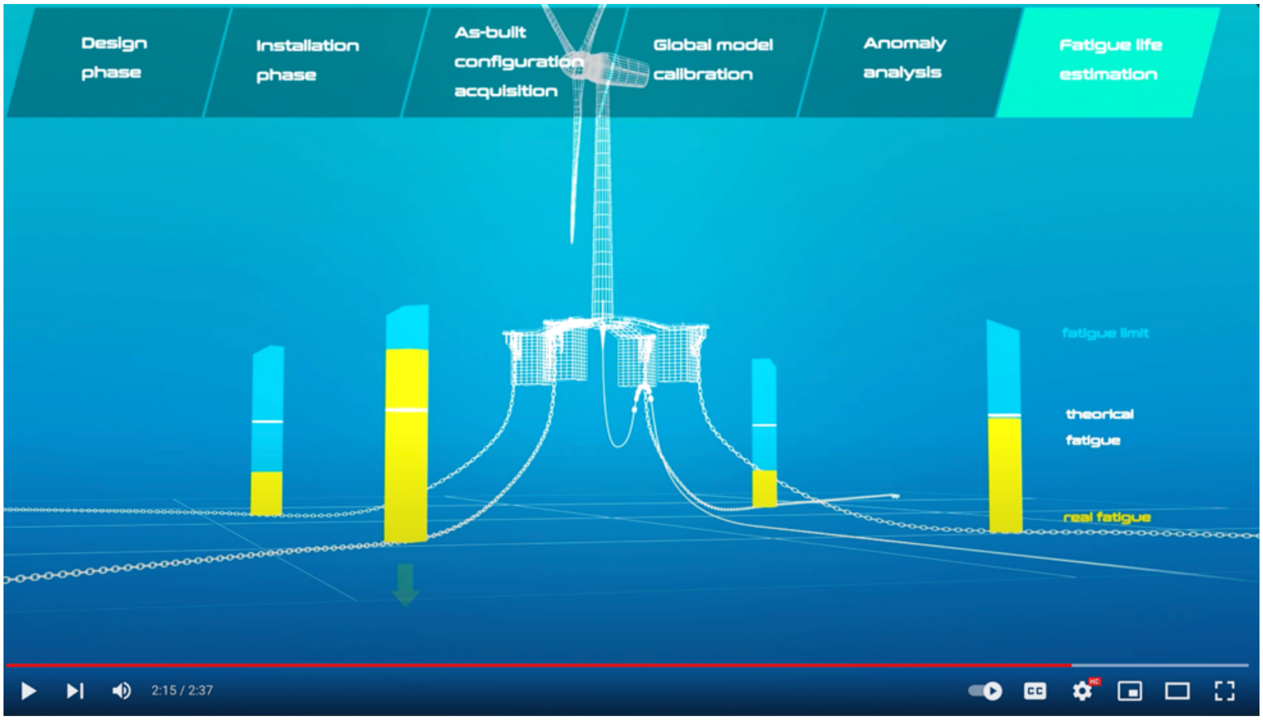


Figure 4: A Digital Twin to Facilitate the Operation of Floating Wind Farms

Source: Click here to see video

Digital twin (DT) technology varies in size from simply a single part to an entire network of systems. Based on size, DT technology is classified into different types of representative levels. There are many different types of digital twins. Four of the more common types follow, using a wind farm as an example, for illustration.

1. **Component Digital Twin:** This is a single component that has a direction impact on performance and function (e.g., wind turbine bearings)
2. **Asset Digital Twin:** This is the next level of digital twin technology. Its purpose is to describe how individual components are functioning within the asset. The Asset Digital Twin collects information either from a single Component Digital Twin or a group of Component Digital Twins (e.g., wind turbine gearbox)
3. **Process Digital Twin:** Moving to the next digital twin technology level, the Process Digital Twin consists of a collection of different but connected assets (e.g., the wind turbine.)
4. **System or Network of Systems Digital Twin:** This level represents the entire system (e.g., a wind farm). At this level, the digital twin can provide insights ranging from the smallest component to the overall system itself.[15]

Unlike Supervisory Control and Data Acquisition (SCADA) systems, digital twins are not simply reactive. They can be used for prediction and forecasting. How this is done is that digital twins are implemented in software. The algorithms used for prediction and forecasting are written based on machine learning (ML) and artificial intelligence (AI).[16] This enables digital twins to simulate “what-if?” and “what’s-best?” scenarios that can predict how physical assets will perform under certain conditions, after which actions and strategies for managing the assets are recommended.[17] The appropriate persons are able to then review these recommended strategies without having to engage with the “real” asset/system counterparts at all.[18] This is particularly useful when operators are not located near the asset. The cost for digital twin technology varies, in accord with the type chosen and the level of data granularity input to the system.[19]

As a predictive maintenance model, digital twin technology integrates various other models such as physics-based models, statistical models, and machine learning/AI models. Through this combination, digital twinning is able to better assess the state of the asset that in turn enables better predictive and reporting capabilities. The first step involves the loading of time series data to the digital twin server. This data is the building block for the next step, which is the development of an ML-based model that works to predict imminent failure based on “fundamental parameters or the performance of external interfacing systems.”[20]

> *“The digital twin itself cannot operate in isolation. It needs complementary and related technologies to function and provide the desired benefits to the clients*.”[21]

Figure 5: Predictive Maintenance for Wind Turbines Using Machine Learning Algorithms
Click here to see video

Digital twins incorporate various technologies, as needed, such as product lifecycle management (PLM), 3D modeling and simulation, manufacturing process management (MPM), manufacturing operations management (MOM), model-based system engineering (MBSE), augmented reality (AR) and/or virtual reality (VR) and/or extended reality (XR), smart automation, IIoT-connected controls and more – depending upon the asset. Implementing digital twin technologies requires advanced smart sensors, IoT and IIoT devices, and software solutions.

The following figure illustrates the interplay between digital twins and the many related technologies. NB: This illustration involves digital twins, in their many forms, but not specifically those involved with wind turbines.

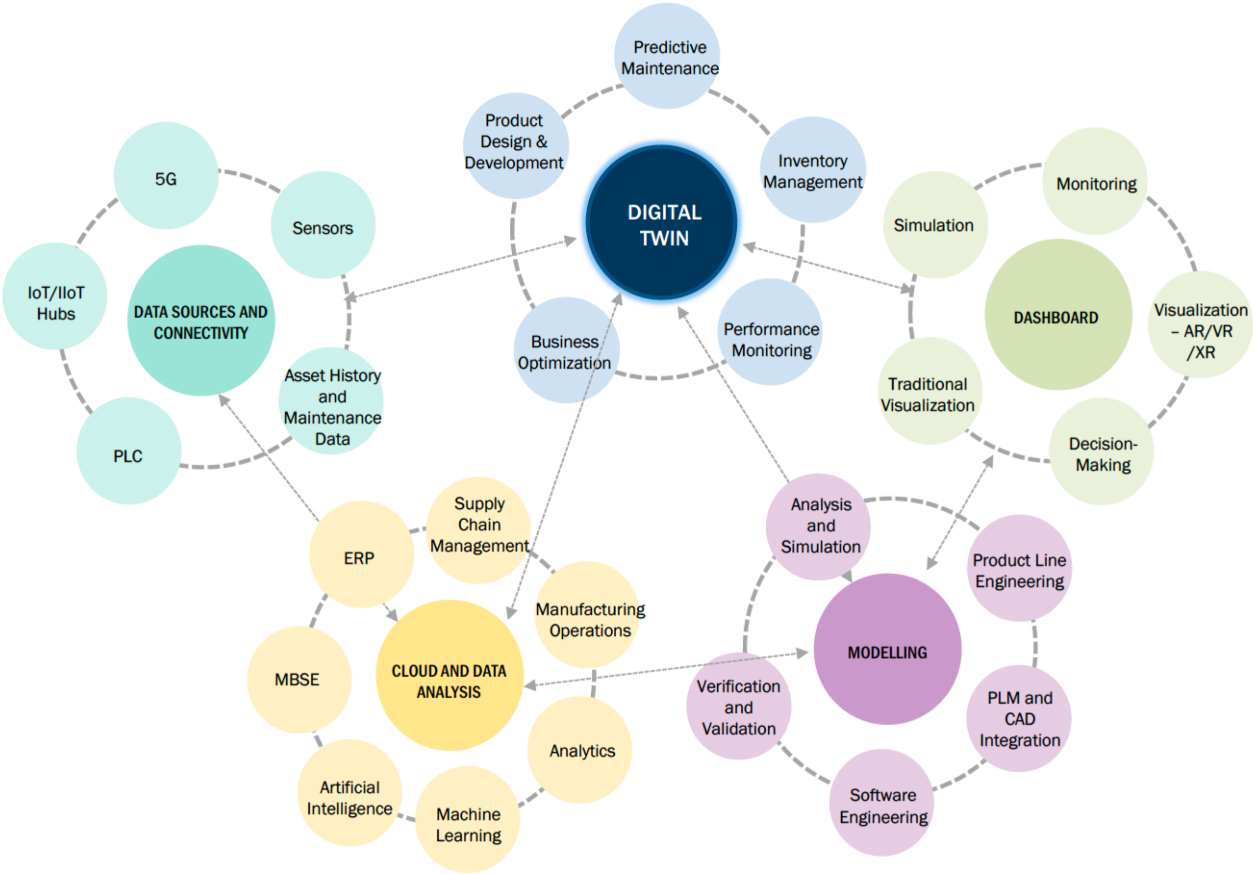


Figure 6: Digital Twin and Related Technologies
Source: Reprinted with permission from MarketsandMarkets[22]

Digital twin technology is forecast to lower the Levelized Cost of Energy (LCOE) for offshore wind farms, at which point wind could become competitive with fossil-based energy.[23, 24, 25] Please note that this is a prediction and data from studies demonstrating a lower LCOE need to be monitored. The digital twin architecture can be represented in numerous ways. The following Figure from the market research firm Frost and Sullivan is another way of representing this.

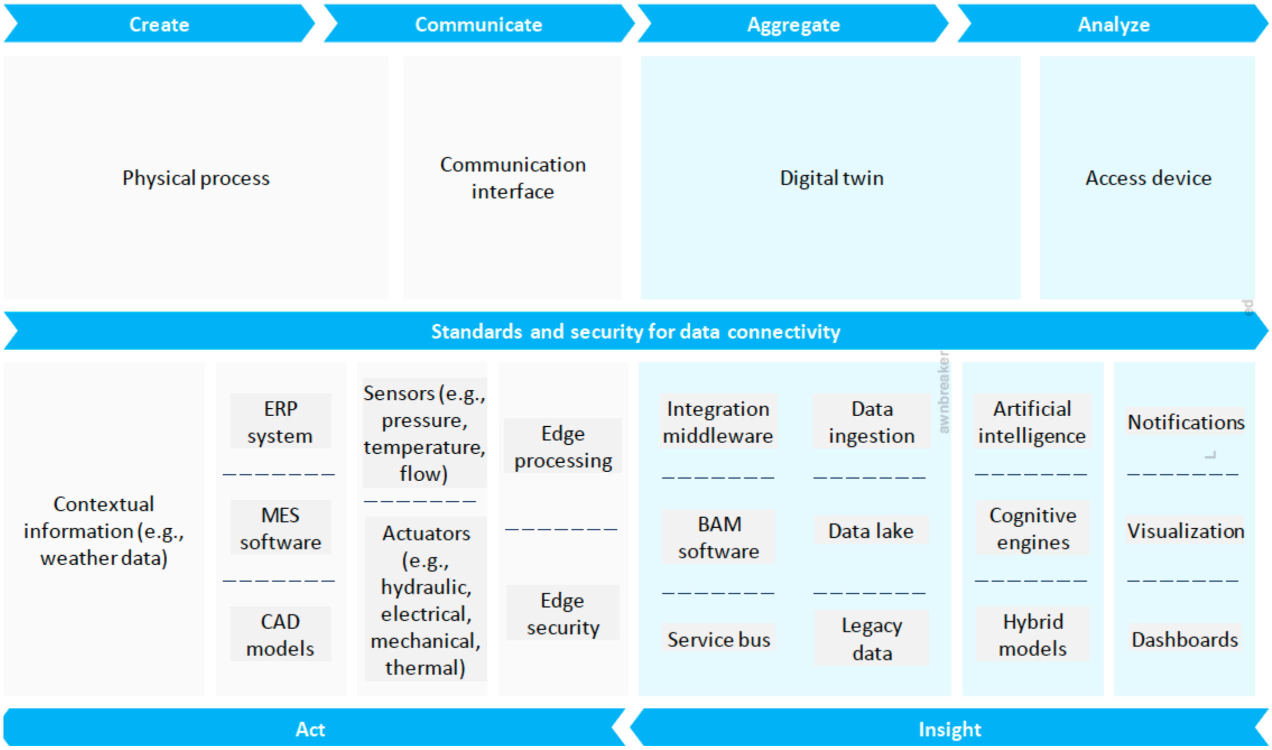


Figure 7: Digital Twin Architecture | Key: Enterprise Resource Planning (ERP); Manufacturing Execution Systems (MES); Computer-Aided Design (CAD); Business Activity Monitoring (BAM).

Source: Reprinted with permission from Frost & Sullivan[26]

4.1 Drawback

A current drawback is that after a digital twin is given all the data necessary to monitor and maintain asset health, "Any change in equipment or asset configuration or operational state would require remodeling of the digital twin, which increases the complexity of maintaining the digital replica. Any modification made to the physical system would require similar changes to its digital model and algorithms. The risk of errors may escalate with the increasing levels of complexity, as the simulation of certain scenarios, such as the addition of new parts at the machine level or operational level changes, may not be precise."[27] GlobalLogic, a Hitachi firm, emphasizes the importance of managing data quality which depends on thousands of remote sensors that must be able to communicate over reliable networks.[28,29]

> **"Any change in equipment or asset configuration or operational state would require remodeling of the digital twin …"**

4.2 Digital Twin Ecosystem

The following figure details the digital twin ecosystem, offering an abundant amount of information – calling out application areas, providers by category, digital twin providers, and more. These are *not* digital twin providers specifically involved with wind turbines and/or wind farms. However, this offers an insightful overview of, essentially, the lay of the land for digital twins and where one might fit within this complex. NB: This figure offers an overall view of digital twins, their many application and technology areas (here listed as categories) with their respective providers/vendors. When viewing the list of digital twin providers and industries (green columns), it is imperative to note these are companies involved in the digital twin space.

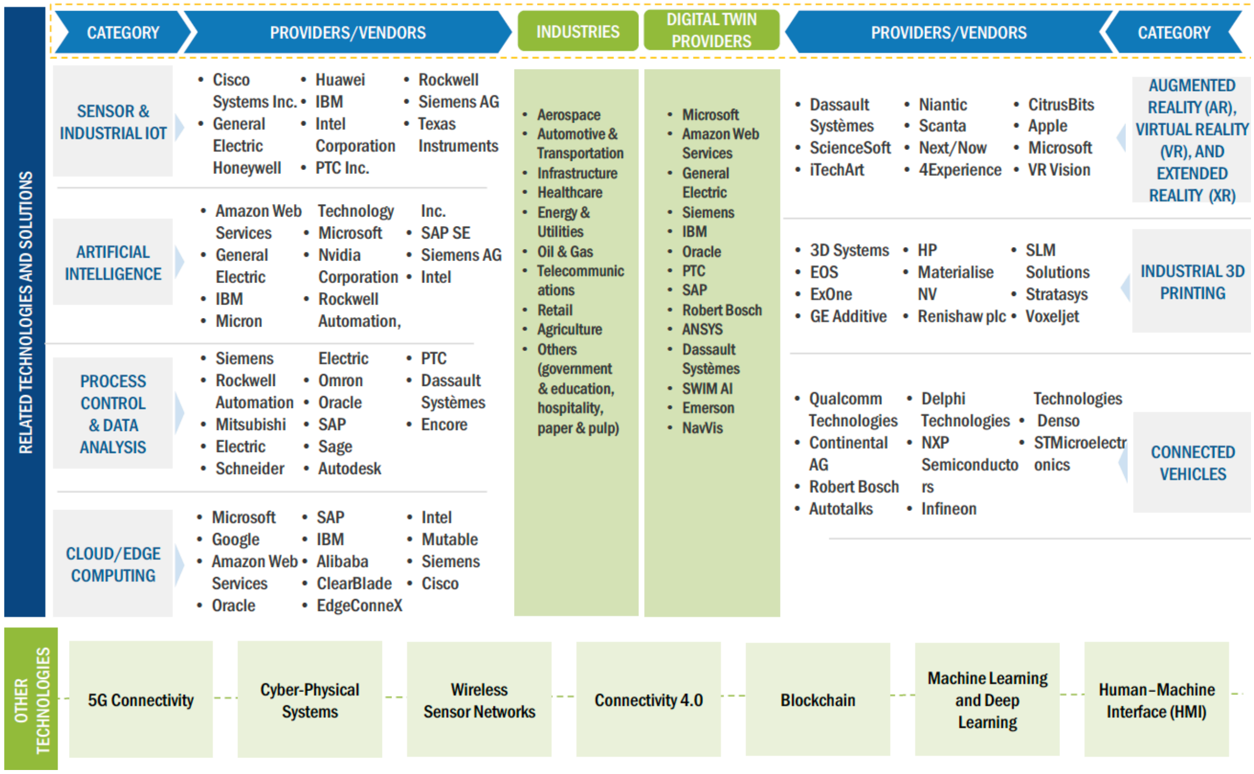


Figure 8: Digital Twin Ecosystem

Source: Reprinted with permission from MarketsandMarkets[30]

Solution providers play a significant role in the entire value chain. The following companies are not only major digital twin providers but also provide supporting products and solutions: GE (U.S.), IBM (U.S.), Siemens (Germany), Schneider Electric (France), SAP (Germany), Oracle (U.S.), ABB (Switzerland), Microsoft (U.S.), PTC (U.S.), and ANSYS (U.S.).

North America is an early adopter of digital twin and related technologies, in part due to the presence of major digital twin providers in the region such as General Electric (U.S.), Bentley Systems (U.S.), IBM (U.S.), Emerson (U.S.), Microsoft (U.S.), ANSYS (U.S.), Amazon Web Services (U.S.), Altair (U.S.), and Oracle (U.S.). *It is reported that these companies are investing "significantly" in the digital twin market*. The top tier (in this case seven companies) in the digital twin market in 2021 were General Electric (U.S.), Microsoft (U.S.), Siemens (Germany), Amazon Web Services (U.S.), ANSYS (U.S.), Dassault Systèmes (France), and PTC (U.S.). Collectively, this group accounted for approximately 50-60% of the entire market share at that time.[31]

Major companies offering digital technology solutions in North America *for power and utilities* include GE, Ansys Inc., Bentley Systems, IBM Corporation, Microsoft, Dassault Systems, and Oracle. "DT [digital technology] utilization for predictive maintenance will be the most sought-after service in the power and utilities industry."[32] Those companies providing digital twin solutions to wind turbine providers include General Electric Digital, Siemens, Ansys, IBM, and Microsoft and will be discussed in detail later in this report.

4.3 Asset Performance Management

Another technology area closely tied to digital twins are asset performance management (APM) systems, which are critical to ensure optimal handling of the power from ever-increasing data. Additional technology "enablers" that enhance management and maintenance capabilities include artificial intelligence (AI), machine learning (ML), big data management, advanced analytics, cloud/edge computing, virtual reality, augmented reality (AR), mixed reality, and intelligent sensors. However, a drawback for APM at this time is "the lack of maturity and application cases of digital enablers" that include digital twins, deep learning, and cloud capabilities. This will limit APM upgrades in the short term. On the other hand, emerging competitive technologies with digital twinning, AI, and/or cloud computing are accelerating the APM market.

Figure 9: Assett Performance Management Software from GE Digital
Source: Click here to see video

What is shaping the market is the growing number of partnerships. Market leaders are focusing on innovative startups that offer next generation capabilities. This is evidenced by an uptick in acquisitions. What is telling is that, over the last two years, the acquisitions primarily targeted "sector-specific software providers in energy control and clean power generation." To illustrate the type of tactical technology partnerships these are, examples of several significant recent acquisitions include the following:

- GE Digital acquired **Opus One Solutions**,[33] a ten-year old software provider that offers advanced grid management. This acquisition enriches GE Digital's portfolio due to its digital twinning capabilities.[34]
- Fluence (an AES and Siemens company) is an APM provider for energy storage and renewable businesses. In late 2020, Fluence acquired the startup **AMS** – an advanced AI-based software provider for energy generation and storage assets.[35]
- Envision Digital acquired the data analytics software provider **QOS Energy**, a company that centrally focuses on managing data from renewable energy sector assets.

Digital twin technologies are one of the main innovation areas of interest to APM providers. Over the past two years, APM leaders have concentrated their R&D, partnerships and acquisitions around real-time simulations and 3D visualization capabilities.

> *"To embrace the complete power of digital twinning, APM providers must refocus their partnerships, acquisitions, and R&D strategies and expand the application scope of digital twins."*

Several examples of acquisitions in digital twin technologies for APM providers include the following:

- Bentley Systems acquired Vista Data Vision, a real-time data visualization and monitoring software enabler.
- In 2021 GE Digital announced new digital twinning analytic features for the company's SmartSignal predictive maintenance software.
- Also in 2021, AspechTech acquired the 3D software provider OptiPlant.[36]

4.4 Trust

According to RenewableUK (formerly known as the British Wind Energy Association), the current trend towards complex, connected systems involving digital twins that capture, store, assess and model predictive outcomes is reliant on two factors: security and trust.

> "Digital twins have historically been met with a mixed response. A lack of trust in their potential is possibly due to incorrect specification, where investment has been driven by the promise of technological capabilities rather than real and well-defined business needs. However, implemented correctly, a digital twin holds incredible potential for helping organizations in the renewable energy industry to reduce costs and risks – and extend operational life. They can become a platform where real-time simulations, advanced artificial intelligence and machine learning combine to collate, analyse, and generate data that supports strategic planning and effective decision-making."

As human operatives are augmented by ML algorithms in the coming years, the focus on validating and assuring the provenance of derived data will increase.

Digital twins are entering the renewable energy space since they offer essentially lifetime optimization for their designated assets. For example, in wind operations, digital twins assist with detecting structural issues (e.g., foundation degradation, rotor imbalance) that can subsequently be repaired. This reduces operating costs, increases energy capture, and extends the life of a wind turbine. Combining physics-based simulation models, which can calculate fatigue accumulation on the main structural components and provide an estimate of the remaining life of a turbine, will identify opportunities to extend life and prioritize inspections and maintenance. Emerging technologies (for example, wind farm numerical models using ML/AI) may impact on future digital twin use cases since these emerging technologies will increase the need for validated data in order to ensure maximum accuracy.

Standardization is essential and will come from increased interaction and cooperation. "This implies open data and data sharing, and the need for information to be in an agreed common format to facilitate data exchange across the supply chain. Building models on standardized libraries is the required foundation of having safe, effective, and efficient digital twins."

> "Even with correctly specified digital twins, problems can arise in operation, as physical assets undergo changes during their lifecycles. *This means companies must also be able to trust that a digital twin will remain fit-for-purpose long after being approved and deployed*. Operators need to be confident that a digital twin is secure and protected against risk (both technical and supply-side) with an emphasis on remaining cyber-secure whilst accurately and reliably monitoring any changes."

RenewableUK states they expect to see "greater focus on validating and assuring the provenance and veracity of derived data in the energy system over the coming years – particularly where human operatives are replaced or augmented by machine learning algorithms baked into digital twins" and ends with the assurance they "believe secure, connected, and trustworthy digital twins with quality assured data value chains will have a crucial role to play within the renewable energy industry and beyond."[37]

DNV, self-described as the "world's leading classification society and a recognized advisor for the maritime industry … delivers world-renowned testing, certification and technical advisory services to the energy value chain including renewables, oil and gas, and energy management … and is … one of the world's leading certification bodies, helping businesses assure the performance of their organizations, products, people, facilities and supply chains."[38]

In response to the question "Why trust matters," DNV made the following statement.

> "Digital twins are powerful tools for optimising the safety and efficiency of systems throughout their lifespan. But the decisions that digital twins empower depend on complete trust in the technology, the data and data processes." [39]

In 2020 DNV partnered with TechnipFMC (a technology service provider to the energy industry)[40] in an effort to develop an industry-first "methodology for qualifying the integrity of digital twin technology" for the oil & gas sector. According to DNV Vice President of Digital Partnering Kjell Eriksson,

> "The attraction is that a digital twin can support information-based decisions across the lifecycle of assets, from the design stage through to decommissioning. *The big question though, is whether the information from a digital twin can be trusted. Establishing such trust will be key to adoption, as companies will only be able to extract maximum value from a digital twin if they are assured that it will function as specified*." [41]

Foundational terms include the following:

1. Establishing trust will be "key" to the adoption of digital twins
2. Maximum value can only be drawn from a digital twin under the condition the user is certain the digital twin will perform as defined
3. An approach that is structured and systematic is required, in order to ensure a balance between performance and expectations. This involves "setting clear goals and managing working processes"[42]

Another example of trust involving digital twins and data was in 2020 when Aker BP and Equinor partnered to develop NOA Fulla and Krafla in the NOAKA area, termed "one of the largest remaining field development opportunities on the Norwegian continental shelf." This development effort included an unmanned offshore platform operated by Aker BP and this is where trust is an issue, since onshore monitoring of the periodically unmanned platform was critical. Aker BP required the services of industrial software provider Cognite, whose industrial DataOps platform – Cognite Data Fusion – "contextualizes operational asset data at scale in real-time. To enable reduced manning without compromising safety, real-time monitoring, control automation and maintenance procedures incorporating remote diagnostics were required." DNV's role was to assess this DataOps platform (Cognite Data Fusion) "following DNV's recommended practice for assurance of digital twins to establish trust in the digital twin-generated data for performance and safety decision-making." DNV's findings were implemented, the outcome of which was that Aker BP could "confidently trust the digital twin of their future unmanned operations."[43]

Figure 10: SLB + Cognite| Delivering data driven solutions at scale for global energy

Source: Click here to see video

4.5 Regulations and Standards

According to a February 2023 Government Accountability Office (GAO) Science & Tech Spotlight on digital twins, “standards and regulations are not fully developed to address digital twin implementation, especially for more complex applications. Currently, users rely on a patchwork of standards for data management, security, and networking established by organizations such as the National Institute of Standards and Technology and the International Organization for Standardization.”[44]

The following table details the various regulations and standards in place globally, as of June 2022 reporting.

Table 1: Digital Twins: Standards and Regulations

COUNTRY	REGION	POLICY NAME	DESCRIPTION
-	Global	ISO/TC 184/SC 4	This standard establishes a framework for the use of industrial data. The scope includes standardization of the content, meaning, structure, representation, and quality management of the information required to define an engineered product and its characteristics at any required level of detail at any part of its lifecycle from conception through disposal, together with the interfaces required to deliver and collect the information necessary to support any business or technical process or service related to that engineered product during its life-cycle.
-	Global	ISO/TC 184	This standard establishes a framework for automation systems and integration. It relates to the standardization in the field of automation systems and their integration for design, sourcing, manufacturing, production and delivery, support, maintenance, and disposal of products and their associated services. Areas of standardization include information systems, automation and control systems, and integration technologies.

-	Global	ISO 23247-1	This standard focuses on automation systems and integration. It also provides an overview and general principles to establish a digital twin.
-	Global	IEEE 1451.4	IEEE 1451.4 defines a physical connection (Mixed-Mode Interface, or MMI) that is alternately used for Transducer Electronic Data Sheet (TEDS) data and analog signals on either 2, 3, or 4 wires. This standard can be used for a wide variety of sensors and actuators.
-	Global	IEEE 1451	This standard establishes the definition and specific requirements for smart transducer interfaces in cyberphysical systems (CPS), industrial internet of things (IIoT), internet of things (IoT), and internet of everything (IoET). In addition, it describes the sensor requirements for smart grids.
-	Global	ISO/IEC 27001	ISO/IEC 27001 is an international standard for information security management. In 2005, the International Organization for Standardization and the International Electrotechnical Commission jointly produced the standard, which was then amended in 2013.
-	Global	ISO 19650	The ISO 19650 standard is an international standard for applying building information modeling (BIM) to manage information throughout the life cycle of a built asset. It is closely related to the current UK 1192 standards and contains all of the same principles and high-level requirements as the UK BIM Framework.
U.S.	North America	NISTIR 8.56 (Draft)	This provides a detailed definition of digital twins, the motivation and vision for their use, common low-level operations, usage scenarios, and example use cases.
U.S.	Global	ISO 19136:2007 GML	It is a standard for exchanging location-based information, addressing geographic data requirements for smart grid applications.
U.S.	Global	IEC 61850	This standard defines communication protocols for intelligent electronic devices at electrical substations.
U.S.	Global	ANSI/ISA95	This ISA standard provides consistent terminology for suppliers and manufacturers to provide consistent information and operations models.

Source: Reprinted with permission of MarketsandMarkets[45]

4.6 Data Sharing and the Legal Implications

Currently, digital twins have been developed and deployed in various applications that include the military, aerospace, power generation, manufacturing, healthcare, automotive industries, urban planning and more.[46] Key markets for digital twin adoption in North America include the military and aerospace sectors.

Digital twins act as a reserve for data from the physical twin. This has legal implications for data sharing and confidentiality.

Due to their intrinsically complex nature, digital twins have immense legal implications. Apart from the intellectual property rights stemming from the digital twin design, there are several other factors to consider. For instance, digital twins act as a reserve for data from the physical twin. This includes specific information detailing the physical asset's design, construction, performance, and depreciation. Data ownership, in particular, is an intellectual property right that is not yet adequately applicable to digital twins. Consider the dilemma within a scenario where a digital twin is designed and operated separately from its physical twin. Another involves the nature of agreements, which "would need to take into account the lifespan of the digital twin. This is because *data access, for instance, should be equally long or longer than the life of the digital twin*. This is because a digital twin will only ever be as good as the data that goes into it."

The legal implications involving data sharing and confidentiality create a legal dilemma, essentially a paradox since without data sharing, digital twins would have no utility. The case is that "intellectual property and legal norms do not account for non-essential data sharing. Especially in complex cases where ownership is already vague." Another issue is liability, considered legally to be one of the most complex issues for digital twins and data sharing. Liability is difficult to prove since digital twins are a composite of connected networks and systems. Imagine the butterfly effect when "changes in one system ripple out to affect the entire model. With multiple users and data sources, errors may be difficult to identify and trace." A solution is offered, which is to create a centralized command center that would serve as gatekeeper and would be tasked with authorizing data changes. "However, even then errors may still occur and be difficult to trace. As such, attributing liability is not so simple." Of particular notice is the statement that, in addition to these various data sharing scenarios, "errors could have originated outside the digital twin ecosystem. *For instance, if sensors on the physical twin are not working accurately*."[47]

In September 2022, the Northrop Grumman newsroom reported on the company's recent signing of an "industry first" – an agreement that Northrop Grumman would share data access across the B-21 Raider platform with the U.S. Air Force. (The fact that this is called an "industry first" and that it involves the military/aerospace sector that has long been involved with digital twins – may, in its own right be telling.)

> *"Northrop Grumman and the U.S. Air Force signed an industry-first data rights agreement recently, opening B-21 data access and collaboration across the program, including the launch of a shared environment for the B-21 digital twin."*

According to a Northrop Grumman spokesperson, "The B-21 Raider is a true digital native, and this data rights agreement coupled with the cloud based digital twin allow us to drive down risk in the EMD [engineering and manufacturing development] phase, will enable rapid capability upgrades and lowers sustainment cost over the life of the program." This agreement "establishes a level of access to common data and data environments that had not yet been accomplished on a program of this scale or this early in the lifecycle. It creates greater transparency and collaboration between Northrop Grumman and the Air Force, helping to deliver greater affordability and rapid upgradability throughout the program lifecycle."[48]

5.0 Digital Twins and Wind Turbines | Wind Farms

A digital twin of a wind turbine with intelligent data processing capabilities enables predictive maintenance of not only the turbine's condition but also its behavior. Digital twins combine mathematical models describing turbine operations by way of the sensor data that are collected and processed. This offers wind farm operators the ability to predict structural failure and make better decisions surrounding maintenance in advance of failure. Consequently, wind farm operators are able to reduce both maintenance costs and downtime during the life cycle of the wind turbines involved. In short, digital twinning improves performance monitoring which bears ultimately on system dependability and availability.[49]

Offshore wind energy data space
based on the IDS standard

Figure 11: IOT Solutions – World Congress 2023

Source: Click here to see video

IoT sensors that collect real-time data and operational status are placed on wind turbines. The collected data are then relayed to a processing system and applied to the digital twin. At this point the virtual model can run simulations, assess performance and offer actions for improvement. This allows wind farm operators the ability to leverage the data from a digital twin to predict performance issues that would require maintenance prior to failure. In addition, "Real time information on how a wind turbine is responding to specific weather data such as air pressure, temperature, wind direction and turbulence intensity can also be used in the development of future digital wind turbines."[50] So, not only does digital twinning work with predictive failure rates but also can assist with more favorable future designs.

IoT sensors bridge the physical and digital world.

The fact that wind turbines are becoming increasingly larger and are being deployed offshore impact on wind turbine operation and maintenance (O&M). The offshore environmental conditions are extremely harsh. For this reason digital twins are now being looked at as a key enabling technology for wind turbine O&M. Digital twins allow for data collection, visualization, and analysis at either the component or system level (i.e., individual turbine or wind farm.)[51] The goal of the digital twin with respect to O&M is to process information based on the network of sensors so that appropriate actions can be taken to prevent catastrophic failure.

As the demand for renewable energy increases, the wind industry is looking for ways to increase its energy production and decrease its levelized cost of energy (LCOE). By increasing the size of the rotor blades, the energy output increases. However, an increase in blade size can put additional strain on the turbine's components and construction.

Blade failure can occur from various conditions, ranging from lightning strikes, blade icing, damage from external objects, etc., to material or power regulator failure and poor design. These failures result in costly repairs and lost income (for the time when the turbines are not in operation). Other components prone to failure include the generator, gearbox, and bearings. The main causes for generator failure are attributed to any or all of the following: weather conditions, wind loads, incorrect installation, manufacturing or design flaws, among others. Nacelle failures are largely impacted by temperature problems, metal parts reacting to moisture (i.e., weakening and/or degrading), hydraulic and cooling system problems, blade icing, and erosion. Vibration anywhere within the asset is problematic.[52]

Wind turbine failure can be divided into two categories: 1) internal; and 2) external. The following figure illustrates the various failures, both internal and external, specific to wind turbines.

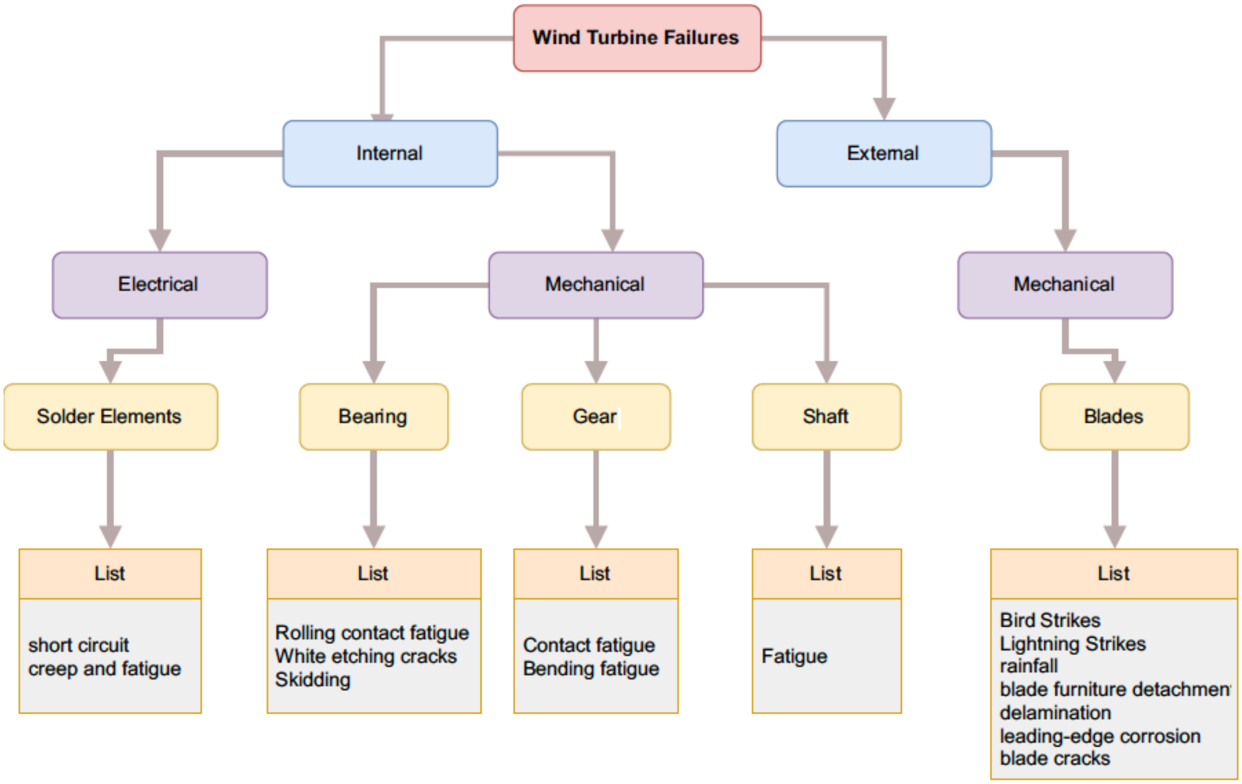


Figure 12: Different Types of Wind Turbine Failures
Source: Energy Informatics, 2023[53]

Adoption Rate of Digital Twin Technology in the Energy Sector

As of 2021 reporting, digital twin technology adoption across the power and utilities industry was in its early stages. From that time, it was forecast that the rate of adoption would accelerate in developed economies in the next 3-5 years (making it 2024-2026) and developing economies in 5-10 years (making it 2026-2031). The focus will be on three application areas: 1) remote monitoring and control (RMC); 2) predictive maintenance and scheduling (PMS); and 3) scenario and risk assessment (SRA) – in order to efficiently manage connected assets across the power industry. With an evolving competitive landscape, it is likely that merger and acquisition (M&A) activities will increase. As digital twin technology matures, companies will pursue "economy-of-scale synergies and enhanced technology offerings." A market driver is the pairing of a decline in sensor costs and the growth of enabling technologies that is likely to have a high impact on adoption for operators and stakeholders.[54] Additional drivers include the rapid growth in smaller chips with higher computational power and nanotechnology enabling even smaller sensors with increased capabilities. Witnessing the increased collaboration between government, research institutions, tech startups, and top-tier companies also will serve to advance enabling technologies (e.g., AI, XR, data analytics, etc.) that will result in further lowering costs.

> "Digital technology vendors may choose to expand in the market by acquiring niche companies or start-ups they nurtured through strategic investments or develop in-house analytics software and hardware abilities. These vendors should also consider partnering with system integrators, OEMs, hardware vendors, and cloud service providers to expand their market presence."[55]

Studies are beginning to be released on the specific challenges offshore wind and complex land terrains face with respect to digital twinning.[56, 57, 58]

6.0 Digital Twins and Wind Farms: Use Cases

Inherent to wind farms are the risks posed by extreme wind. Wind farm equipment can experience vibrations that can lead to fatigue, wear and tear, and structural damage if not checked. Typically, wind equipment does have built-in mechanisms that can help minimize damage during strong winds.[59] One example of this is that a turbine's angle of inclination and blade speed can be automatically adjusted. Another is that the system can shut down automatically. While these built-in mechanisms can be effective – to an extent – they may not have the capability to react quickly enough to ensure continued performance. This is where digital twins offer an advantage. Not only can digital twinning assess real-time performance and also predict imminent failure, this technology also plays a significant role in safety for the persons involved with response and repair. By employing a digital twin, there is no need for technicians to be sent out to diagnose a fault. Instead, this would be done remotely, after which the technicians would carry out repairs at the precise site where intervention is necessary.[60]

Figure 13: Extreme Conditions: Can Wind Turbines Survive Tornadoes Wind Speeds
Source: Click here to see video

Over a lifespan of approximately twenty years, the average wind turbine requires maintenance checkups two to three times a year. Inspecting wind turbines can be difficult, especially if they are located offshore or in remote locations. Scheduled maintenance is not responsive to any alert that it may be needed, the outcome of which is that potential defects can be overlooked.[61]

6.1 GE Renewable Energy: Digital Wind Farm

According to GE Renewable Energy's Digital Wind Farm: The Next Evolution of Wind Energy brochure, "In wind farms, digital twins are being used to display wind patterns, electrical output, and wear and tear on equipment. They help improve the efficiency of operations. For instance, GE (U.S.) has initiated the Digital Wind Farm project built on the Predix platform. This software platform creates digital twins of a windmill, which comprise a digital infrastructure for the wind farm, enabling operators to collect, visualize, and analyze unit- and site-level data. Through the constant collection of this data, component information, service reports, and performance data of similar wind turbine models can be obtained from the predictive model for the digital twin. These predictive models serve as the basis of the new design and simulation applications, allowing wind farm operators to optimize maintenance strategy, improve reliability and availability, and increase annual energy production."[62]

GE's Digital Wind Farm consists of two parts: 1) a 2MW wind turbine; and 2) wind power software. The software serves to "monitor and optimize the turbine as it runs and generates energy."

> "The Digital Wind Farm starts with the digital twin, a cloud-based model of a wind farm. With digital twin technology, engineers can mix and match up to 20 different turbine configurations to make sure they are building the best wind turbine possible for the real-life location of the farm. Once the physical wind turbine is installed, the digital twin model can really get to work—collecting and analyzing data from its real-life counterpart, and providing suggestions to make it even more efficient."[63]

Figure 14: Minds + Machines: Meet a Digital Twin GE Digital
Source: Click here to see video

When considering that the average lifespan of a turbine is approximately twenty years, depending on environmental factors, by integrating the hardware with the wind energy software, "GE has demonstrated the technology can help to increase production by around 20% and create an additional $100m in revenue over a turbine's life cycle."[64]

6.2 Clearway Energy Group (California)

Clearway Energy Group (California) deployed a digital twin on the wind farms they operate to predict the behavior of their wind turbines. This was done to assist operators to determine whether or not their systems were strong enough to carry a strong wind load, since their systems need to provide energy without interruption. The digital twin runs performance simulations during various wind speeds, after which it predicts performance in these conditions by using data from weather conditions and sensors from the wind turbines. Benefits from digital twinning include more reliable wind turbines as well as improved safety for engineers since they can diagnose faults remotely versus having to do this at the site.[65] Clearway's wind portfolio includes 6 GW+ in development of both new and repower wind projects that span California, Colorado, Idaho, Maryland, Maine, Montana, New Mexico, Texas, Washington, West Virginia, and Wyoming.[66]

Figure 15: Clearway - Black Rock Wind Farm in West Virginia

Source: Click here to see video

6.3 Bentley Systems

Bentley Systems is an infrastructure engineering software company that offers digital twins technology that is built on Microsoft Azure. Bentley Systems has been a Microsoft partner since 1984. It is this nearly forty-year relationship with Microsoft that provides Bentley "access to the full modern Azure cloud technology stack so that its product teams can continuously incorporate new capabilities and deliver domain expertise across the industries it serves."[67] The company's iTwin service (supported by Azure Digital Twins and Azure IoT Hub) "rapidly ingests and models large amounts of complex operational data from wind turbine IoT sensors and other sources."[68] By using Bentley Systems' proprietary simulation tool, iTwin Services, users are able to create a digital twin environment that is real time, visualizes data in mixed reality and employs artificial intelligence (AI) to assist with enhanced data evaluation and more efficient decision making.[69]

According to a June 2021 Microsoft case study on Bentley Systems, the statement was made “Bentley recently committed to funding a multimillion-dollar investment to accelerate infrastructure digital twin technology by helping grow an ecosystem of developers and partners to apply digital twins across multiples industries and domains. The company offers a comprehensive range of world-class integrated solutions tailored to meet the demands of multidiscipline project teams in a wide range of industries.”[70] Microsoft and Bentley Systems are founding members of the Digital Twin Consortium.[71]

The following presentation video was given by Bentley's Senior Offshore Product Manager Mark Upston at the 2020 Reuters Offshore Floating & Wind Europe Digital Conference.

Figure 16: A Digital Twin Solution for Design and Operation of Offshore Wind Turbine Platforms

Click here to view video

An example of digital twinning and its impact on wind farms is the case of Doosan Heavy Industries & Construction (South Korea) partnering with Microsoft and Bentley Systems to develop a digital twin of the company’s wind farms. For a sense of scale, Doosan currently has sixteen South Korean wind farms in operation that generate enough electricity to power approximately 35,000 homes annually. The South Korean government appointed Doosan to take part in helping the country meet its Green New Deal plan’s target of generating 20% of the country’s electricity from renewable sources by 2030.

> “Seeking improvements in the efficiency of their wind turbines, Doosan Heavy Industries & Construction partnered with Microsoft and Bentley Systems to develop a digital twin of its wind farms that helps it maximize energy production and reduce maintenance costs. Leveraging Azure Digital Twins and Azure IoT Hub powered by NVIDIA-accelerated Azure AI Infrastructure capabilities, Doosan

> can simulate, visualize, and optimize every aspect of its infrastructure planning, deployment, and ongoing monitoring."[72]

Doosan employed Azure Digital Twins' flexible modeling capabilities to develop comprehensive digital models that combine data from IoT sensors on wind turbines, weather data, and predicted power output. The Bentley iTwin program then combines this data with 3D and 4D CAD models, as well as reality models, to build entire solutions that will transform the way infrastructure projects are conceived, built, and operated.[73]

Figure 17: Doosan Wind Farm Digital Twin: Visualizing IoT and Machine Learning

Click here to watch video

7.0 Digital Twin Platforms: Technology Providers (Wind)

This section offers information on various digital twin technology providers, each of which is involved with wind applications.

7.1 GE Digital

GE Digital offers digital twin technology along with associated services for various industries that include power and utilities, oil & gas, manufacturing, aviation, and more. The company's digital twinning runs on its industrial platform named Predix^{TM} (now Edge Analytics Enabled) that is able to handle massive volumes of data from multiple sources from which it executes analytical models. Service offerings include research and development (R&D), real-time remote asset management, predictive maintenance, and scenario modeling.[74] Platform features include IT/OT connectivity, data processing fabric ("streaming and batch data ingestion and the near real-time data and analytics processing to handle a variety of application needs"), analytics execution, edge-to-cloud security and cloud scalability. GE Digital application features are functions that include data visualization, dashboarding, alerting, case management and more, serving to support APM (asset performance management) and other application workflows."[75]

Figure 18: What is a Digital Wind Farm?
Click here to see video

7.2 Siemens | Siemens Gamesa

Siemens develops digital twin technology by way of its MindSphere IoT platform that enables users to build, test, and integrate digital twin environments with increased flexibility and efficiency.[76] Siemens offers digital twin technologies that can be applied from initial prototyping through commissioning, implementation, operation, maintenance and servicing. The company's MindSphere offering is a cloud-based, open Internet of Things (IoT) operating system that connects wind turbines to allow for the use of data via IoT for analysis. The open IoT MindSphere platform supports "the initialization of a continuous improvement process" through all phases the life cycle of wind turbines, said to achieve this by loading actual operating data back into the development process.[77]

In March 2022 it was reported that Siemens Gamesa Renewable Energy partnered with NVIDIA to create "physics-informed" digital twins of wind farms. How this will be done is that "Virtual representations of Siemens Gamesa's wind farms will be built using NVIDIA Omniverse and Modulus, which together comprise NVIDIA's digital twin platform for scientific computing. Virtual representations of Siemens Gamesa's wind farms will be built using NVIDIA Omniverse and Modulus, which together comprise NVIDIA's digital twin platform for scientific computing." To get a sense of computing scale, by using NVIDIA Modulus (an AI-based framework for developing physics-informed ML models) paired with Omniverse (a 3D design "collaboration and world simulation platform"), researchers are able to simulate computational fluid dynamics "up to 4,000x faster than traditional methods — and view the simulations at high fidelity."[78]

This partnership explored the impact of turbine placement, where one turbine can change wind flow and create wake effects that reduce productivity.

Figure 19: Maximizing Wind Energy Production Using Wake Optimization
Source: Click to see video here

7.3 Ansys

Ansys offers wind turbine simulation solutions that encompass design and development, siting, and operation and maintenance (O&M). Under wind turbine design, Ansys states the company offers "Comprehensive wind turbine simulation, from embedded software to siting, predictive maintenance and digital twins." Under O&M, by the use of "virtual sensors, the use of 3D reduced order models and what-if scenario simulations, a digital twin of a wind turbine can be generated to optimize performance and maintenance requirements and scheduling."[79]

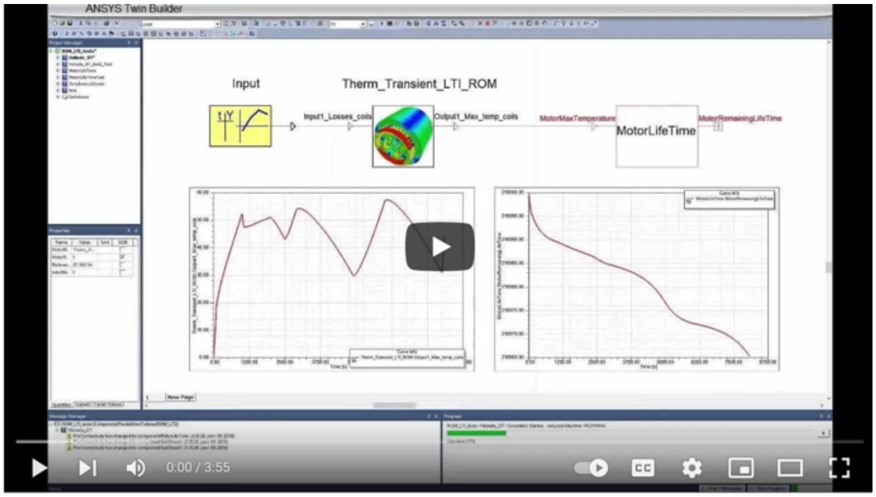


Figure 20: Twin Builder Used to Create a Digital Twin of GE Offshore Wind Turbine
Click here to view video

7.4 IBM

According to IBM, “Digital twins of wind turbines, solar panels or entire renewable energy grids have the potential to improve overall performance, making these energy sources more competitive with fossil fuels.”[80] IBM offers enterprise-wide digital twin solutions through its IBM Maximo Enterprise Asset Management offering. Using the IBM Maximo platform, companies can design, monitor, and test digital twin environments virtually and also integrate digital twins quickly into operations. The company sells digital twin platforms to its customers through its IBM Digital Twin Exchange.[81] A brief description of the IBM Digital Twin Exchange follows.

> “The IBM Digital Twin Exchange offers an e-commerce platform for third parties selling and buying digital twin assets. Digital twin providers pay an annual membership fee for the opportunity to upload and list their digital twins in the IBM Digital Twin Exchange for sale to users. IBM retains a percentage of any digital twin sale. Digital twin buyers can peruse category menus and search using keywords and filters to find a particular digital twin. Buyers can search by industry, manufacturer, and price. Digital twin buyers can peruse category menus and search using keywords and filters to find a particular digital twin. Buyers can search by industry, manufacturer, and price. Eligible users may add an asset to a shopping cart, proceed to the checkout section, and purchase the digital twin using IBM Digital Twin Store Credit, which can be purchased by customers to acquire digital twins. The ability to purchase a digital twin through the IBM Digital Twin Exchange is currently available for U.S. customers only.

> A reviews section can help buyers evaluate digital twin assets during their selection process. Buyers also can submit requests for digital twins, and IBM Digital Twin Exchange support members will engage manufacturers to request they make certain digital twins available for sale in the IBM Digital Twin Exchange. The IBM Digital Twin Exchange is a resource for asset-intensive industries, including organizations managing enterprise-wide digital assets with solutions like IBMMaximo Asset Management. Manufacturers can easily add their digital twin content in bulk, manage their inventory, and establish pricing for their assets."[82]

7.5 Microsoft

Microsoft delivers digital twin technology, solutions and services through its Azure Cloud Computing Platform. This platform offers users the capabilities to build, test, and integrate digital twin solutions that can replicate physical environments to generate simulations illustrating the interactions between the various systems involved – essential for scenario modeling and more effective decision making.[83] In November 2021 it was reported that Vestas Wind Systems A/S was looking to optimize wind energy production by reducing the negative impact of turbine wakes. This led to a partnership involving Microsoft and minds.ai. Vestas ran a "reinforcement learning engine using machine learning and Microsoft Azure high-performance computing and storage resources." With proof of concept complete, Vestas is said to now have the tools necessary "to generate simulations that offer the potential to help wind farms mitigate wake effect, generate more wind energy, and build a sustainable and prosperous energy future."[84]

8.0 Digital Twins and Sensors

Digital technologies are already transforming the global offshore wind market. Emerging technologies and the offshore wind industry's demands for turbines with greater operational efficiency, flexibility, and total cost of ownership reduction will influence TaaS (testing as a service) and solution-based revenue models. Digital twins allow OEMs (original equipment manufacturers) and Internet service providers (ISPs) to simulate the operations of their offshore wind assets/systems in real time under different operational scenarios. This helps them to make clear, informed decisions, improves operations, and reduces operational costs and downtime. In addition, this enables the smooth functioning of the wind fleet and controls damages from natural calamities. As the offshore wind market grows and the competition increases, OEMs have started investing in supply chain solutions and combining emerging technologies to focus on multi-brand servicing to increase their share of the O&M market.[85]

The Floating Wind Joint Industry Project (FLWJIP) is a partnership involving the Carbon Trust (a global climate market consulting group) and seventeen offshore wind developers. Since its founding in 2016, the Floating Wind JIP has completed two phases (Phase I and Phase II), each of which consisted of studies outlining critical needs for the area under investigation to reach cost parity with other energy technologies. Stage I involved an initial review of policy needs, technology status and cost status for floating wind, the outcome of which formed the basis for selecting several key technical challenges for investigation in Stage II. Its Phase III Summary Report: Floating Wind Joint Industry Project was a summary of the research undertaken by the Floating Wind Joint Industry Project (FLWJIP) to provide both technical opportunities as well as technical challenges relating to offshore wind as it moves towards commercial-scale wind farms.

The FLWJIP group's Phase IV Summary Report is a summary report that reviewed progress made for four key research areas in place between 2020 and 2022 and also offered a market overview for floating wind. Within the section discussing "Innovation/technology needs," digital twins and floating offshore wind was addressed. The specific innovation called out was to "Apply recent research on sensor placement strategies to gather data on FOWTs [floating offshore wind turbines] to validate modelling software tools." The outcome of this discussion follows.

As of 2022 reporting, software tool validation has mostly been based on "code-to-code comparison or comparing model code with results from small-scale experiments." However, when taking into consideration that more floating wind farms are underway, the opportunity arises for large-scale validation using various modeling technologies/tools.

> "The more innovative floating substructures are, the more important the validation of the software used in the design process becomes. Current innovations which require full validation of software include: singlepoint mooring concepts with turret, tower-less concepts (three struts replacing tower), suspended keels, synthetic moorings, non-redundant design approaches and advances controllers."

These types of functions typically are implemented by way of state-of-the-art software tools where the level of functionality is proven by scaled experiments employing a select number of FOWTs. Notably, "For this to happen, these FOWTs must be fitted with sensors in the correct positions." When looking at the various sensor types required to achieve this, these sensors include accelerometers (for motion capture) and strain gauges on structural elements (capturing elastic deformations). In addition, differential global positioning system (GPS) sensors capture rigid-body motions.

> "For FOWTs, the approaches of fixed-bottom foundations for mechanical load monitoring can be partially adopted. As for jackets and monopiles, the dominant elastic modes have to be identified and the sensors placed such that the locations of largest deformations are well captured by accelerometers."

The key takeaway from this discussion is the following advocacy – "Augmentation of structural sensors with digital twins is also advisable for FOWTs, due to some inaccessible components, which are impractical to instrument with sensors on the market."

The Figure below illustrate a potential sensor placement strategy for a semi-submersible FOWT. The objectives of this strategy target the following.

Measurement of structural sectional forces via strain gauges at:

- Blade-root
- Yaw bearing
- Tower-base (bolted flange connection)
- Joints of tubular members, pontoons (covering Vortex-Induced Vibration (VIV))
- Midpoints of tubular members, pontoons
- Vicinity of mooring line attachment point to reconstruct mooring tensions
- Heave plates (radial loads)

Measurement of modal deformations via accelerometers at midpoints and endpoints of elastic members: struts, tower, blades

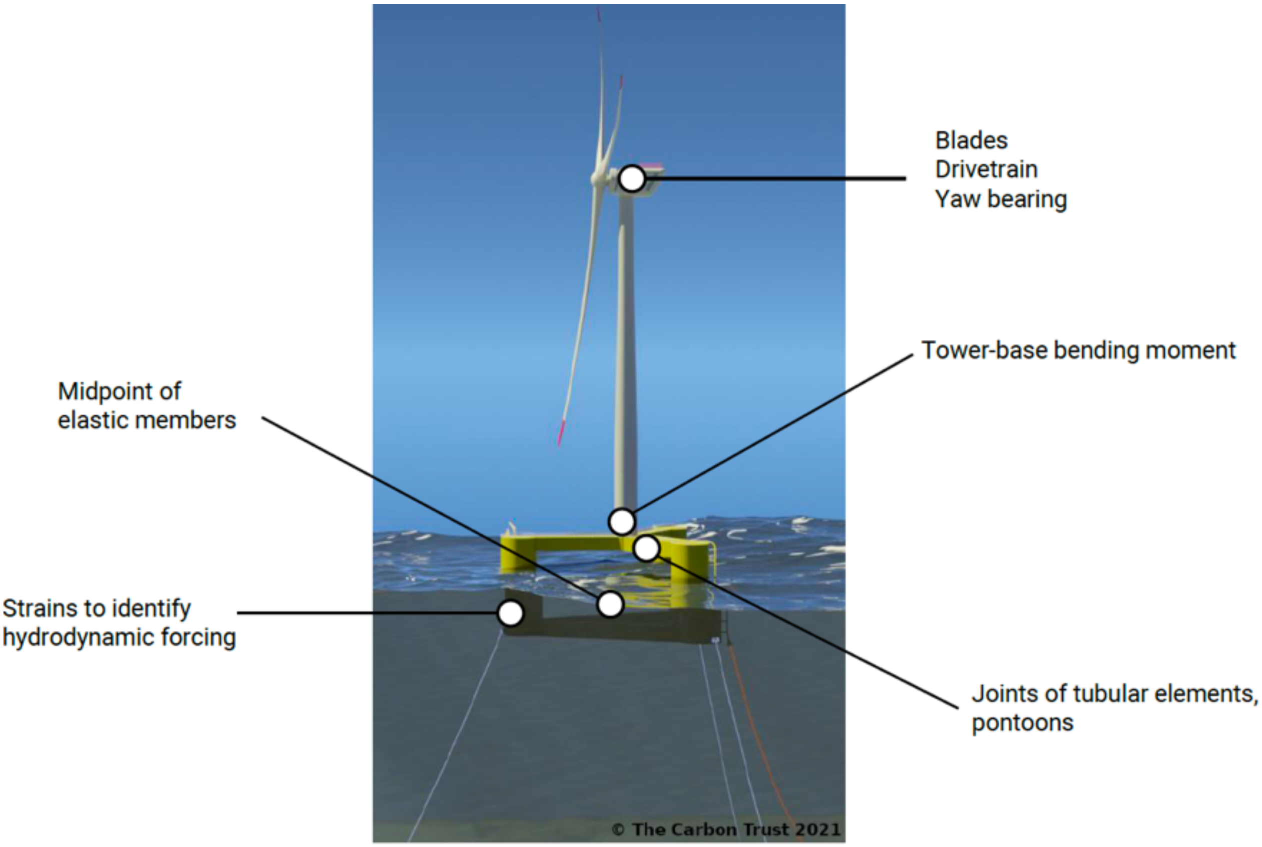


Figure 21: Example FOWT Showing Potential Placement of Mechanical Sensors - Strain Gauges and Accelerometers

Source: Carbon Trust[86]

9.0 Conclusion

As noted throughout this report digital twin technology as applied to the wind industry holds both great promise and numerous challenges. On the one hand, digital twins could reduce cost, assist in the early detection of structural issues and extend operational life. However, this technology must be kept current as conditions and performance of the various assets change. Here, enters the issue of trust.

Legal issues also arise as data sharing is vital for this model to flourish. Today, this appears to be addressed by vertical integration in the wind industry by the primary players. Start-ups with compelling digital twin technology such as Opus One, AMS, Vista Data Vision and others make good acquisition candidates. Although offshore wind is anticipated to grow rapidly during the next several years, the equity investor community appears to be taking a wait and see attitude given the numerous challenges that exist in realizing the goals that the Biden Administrations have posed for growth.

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