Digitalising Floating Offshore Wind

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Cover: Photo courtesy of SWE, University of Stuttgart | Pictured is a nacelle-based lidar for power-performance testing and monitoring on top of the Floatgen demonstrator. The work was performed in the VAMOS project which is funded by the German Federal Ministry for Economic Affairs and Energy (BMWi), and the installation is supported by the Marinet2 H2020 Framework Programme at the SEM-REV test infrastructure.

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Acknowledgments

WFO's 110+ members represent the entire offshore wind value chain including but not limited to utility companies, project developers, manufacturers, service firms, consultancies and other non-profit organisations.

This document is the result of about one year's worth of monthly discussions between participating WFO members of WFO's Floating Offshore Wind Committee (FOWC) on the topic of digitalising the floating wind O&M phase. Thanks to the Committee's digital format, speakers from industry and academia across the world shared their work and views. An internal literature review on the topic was run in parallel. WFO would like to thank everyone who has contributed their time and expertise during the meetings and discussions carried out for this study.

Disclaimer

The views in this report do not necessarily represent the views of all WFO members but are based on a synthesis of recorded insights undertaken by WFO and the WFO O&M Subcommittee Chair over the last year. The findings are also designed to serve as a general account of the digitalised O&M strategy and therefore are subject to evolve along with the industry.

Summary

The goal of digitalisation in floating wind O&M is to create a condition monitoring and inspection plan that gives unprecendented visibility on the wind farm's condition and optimises preventive maintenance, thereby lowering OPEX. The digitalised O&M strategy enhances the integrity management approach used to minimise the probability and consequence of unpredicted failure. The selection of digital tools is done in relation to the integrity management plan's risks assessment. Over the life of the wind farm, the risk-based approach is supported by the data of the monitoring and inspection framework to make more efficient use of maintenance resources.

There are three categories of tools: condition monitoring, inspection technology and digital twins. There is innovation across all categories such as new sensors, inspection vehicles or more broadly the use of artificial intelligence to improve modelling accuracy, data analysis and facilitate human tasks. In this paper, particular attention is paid to digital twins, the newest concept in the context of floating wind O&M. Definitions of the term can vary, but in this White Paper, a digital twin is a model that digitally replicates a physical asset's condition (structural integrity, performance, met-ocean parameters etc.) in a *comprehensive manner* and in *real time*. With these two characteristics, digital twins augment the classic monitoring approach used in offshore industries.

As much as the potential of digitalisation in O&M is already understood by some project developers, classification societies, insurers and financers alike, there are barriers to its proper implementation. These bottlenecks range from technical (low track record of a comprehensive approach, lack of standard rules for systematic model verification and validation at scale) to commercial (unclear cost-benefit, fragmented supply chain, data siloes between OEMs). Just like for any innovation, the first mover risk applies to digitalising floating wind O&M. A call for a comprehensive solution on a commercial-scale project is key to trialing the approach; it would incentivise the supply chain to meet project needs from product offering to the ways data is shared for a holistic digital twin. Until this point, the validation of new modelling approaches on pilot projects continues to be important for building track record.

The requirements for commercial-scale floating wind are different than those of offshore oil & gas or bottom-fixed wind. Realising them implies a few fundamental mindset changes. First, data transparency: data is the basis of a digitalised O&M strategy and stakeholders need to collaborate to build a cost-effective, comprehensive monitoring solution. Second, a focus on advanced condition monitoring over equipment redundancy: compared to oil & gas which focuses on equipment redundancy, improved floating wind asset visibility thanks to digitalisation can help lower safety factors and/or redundancies of the components being monitored. Significant cost savings are expected as a result. This may be the more appropriate path for our industry's risk profile characterised by multiple units with lower margins and reduced safety or environmental risks.

In this paper, we have built a consolidated temperature check of a currently fragmented segment of the industry. We hope to make more accessible the vision for how digitalisation is transforming conventional approaches to unlock higher efficiencies an ultimately lower our

industry’s levelised cost of energy. The floating wind commercial scale projects currently under development can take advantage of this opportune time to properly build digital tools and methods into their design and reap their benefits to the fullest.

Acronyms

WFO – World Forum Offshore Wind
FOWC – WFO’s Floating Offshore Wind Committee
O&M – Operation & Maintenance
FOWT – Floating Offshore Wind Turbine (comprising the floater, turbine, cable and station-keeping system)
CAPEX, OEPX – CAPital EXpenditure, OPerational EXpenditure
LCOE – Levelised Cost of Energy
WTG – Wind Turbine Generator
OEM – Original Equimpent Manufacturer
KPI – Key Performance Indicator
SCADA - Supervisory Control and Data Acquisition

From *Figure 5. Master figure of the typical sensors, inspection methods used on a FOWT*:

CCTV – Closed-Circuit TeleVision
(F)LiDAR or (f)lidar – (Floating) Light Detection and Ranging
GNSS – Global Navigation Satellite System
GPS – Global Positioning System
IMU – Inertial Measurement Unit
MRU – Motion Reference Unit
SSTDR – Spread Spectrum Time Domain Reflectometry

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1 Introduction

The world is entering a new era of digitalisation known as Industry 4.0 where technology is expected to transform our ways of work. Connectivity, analytics, robotics and human-machine interactions are some of the key areas where progress is extending beyond the realm of possibility. For renewable energy technologies, Industry 4.0 is set to reduce costs and integrate production technologies, grids, end-uses and storage for a more performant, affordable and flexible decentralised energy system.

One underlying principle of digitalisation is the need to work with volumes of data we have never seen before, often referred to as "big data". Advancements in big data methods include more efficient storage and software architectures that incorporate edge and cloud-based computing. Together, these are ensuring that the industry is capable of manipulating and interpreting larger amounts of information in real time.

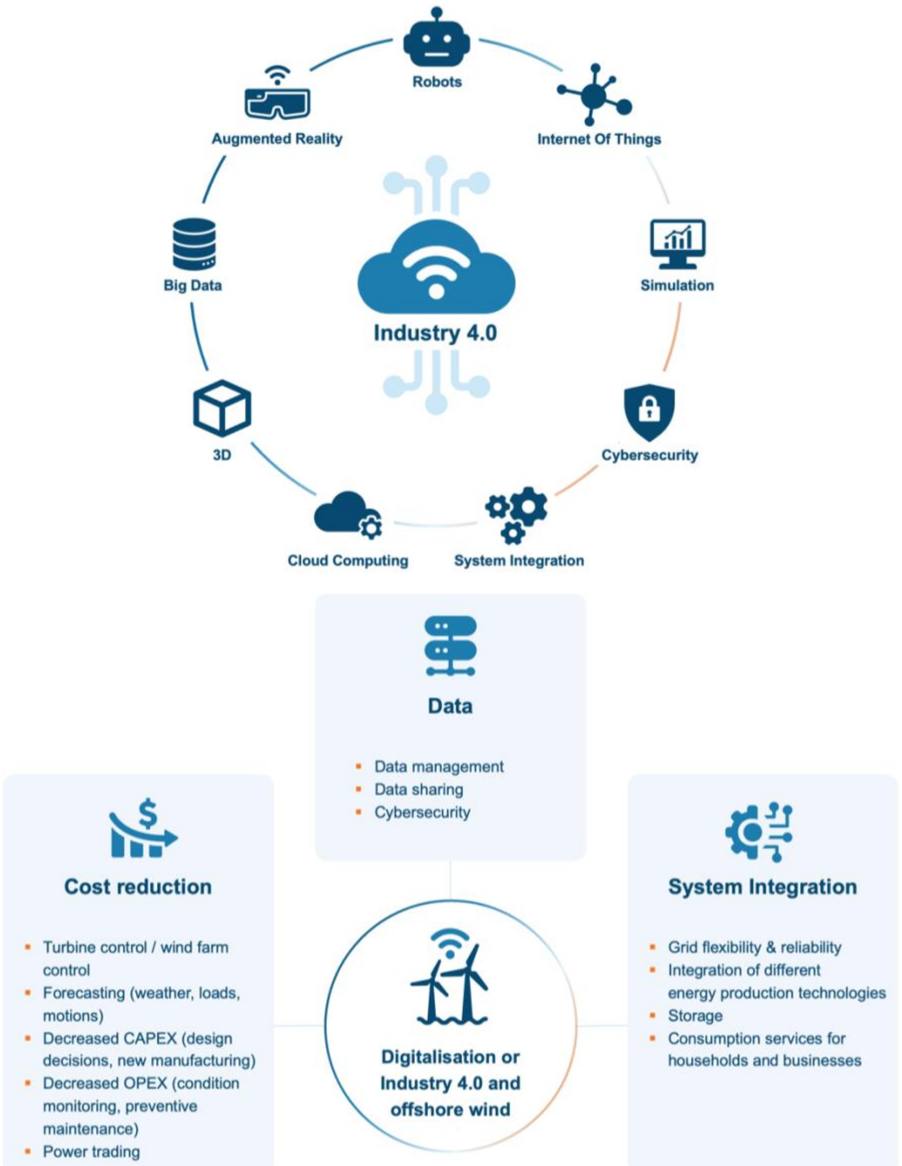

Figure 1. The different parts of Digitalisation or Industry 4.0 (top) and its applications in wind energy (bottom). Definitions of some of these terms in Appendix. Source: PEAK Wind & WFO

Digitalisation is one of the keys to reducing the LCOE of floating offshore wind. Compared to bottom-fixed offshore wind, floating wind is more complex from the design phase all the way to operations. There is not yet a standardised approach for any of the project activities. Adopting a holistic engineering approach is particularly emphasised so that design decisions make for robust yet cost-efficient construction, installation and maintenance campaigns as well as reduced negative impacts to communities and the environment.

While digitalisation can support all project phases, WFO's Floating Wind O&M Subcommittee specifically explored the impact of Industry 4.0 on the O&M or asset management phase. The value of digitalisation in this period is clearly manyfold, with the common thread being that the tools generate actionable insights on the wind farm. In other words, a complex back-end that would initially require specific technical knowledge to interpret is translated into a simple front-end that can be used by a more diverse pool of talent.

This paper demonstrates that mastering a digitalised O&M phase is more broadly a key enabler for investments in commercial-scale floating wind (projects above 250 MW). Just like for major component replacement (White Papers 1 and 2), these O&M decisions must be thought of from the start of the project for the industry to progress as a whole, be it for managing risk (technology, contract, procurement), showcasing bankability, or leveraging insurance.

2 Digitalising Floating Offshore Wind O&M

Digitalisation for floating wind O&M can be organised into three categories of tools: Condition Monitoring System (CMS), Inspection Technology and Digital Twin (DT). In this paper, the term "digitalised O&M strategy"[1] is used to define the combinations of tools that a project may use.

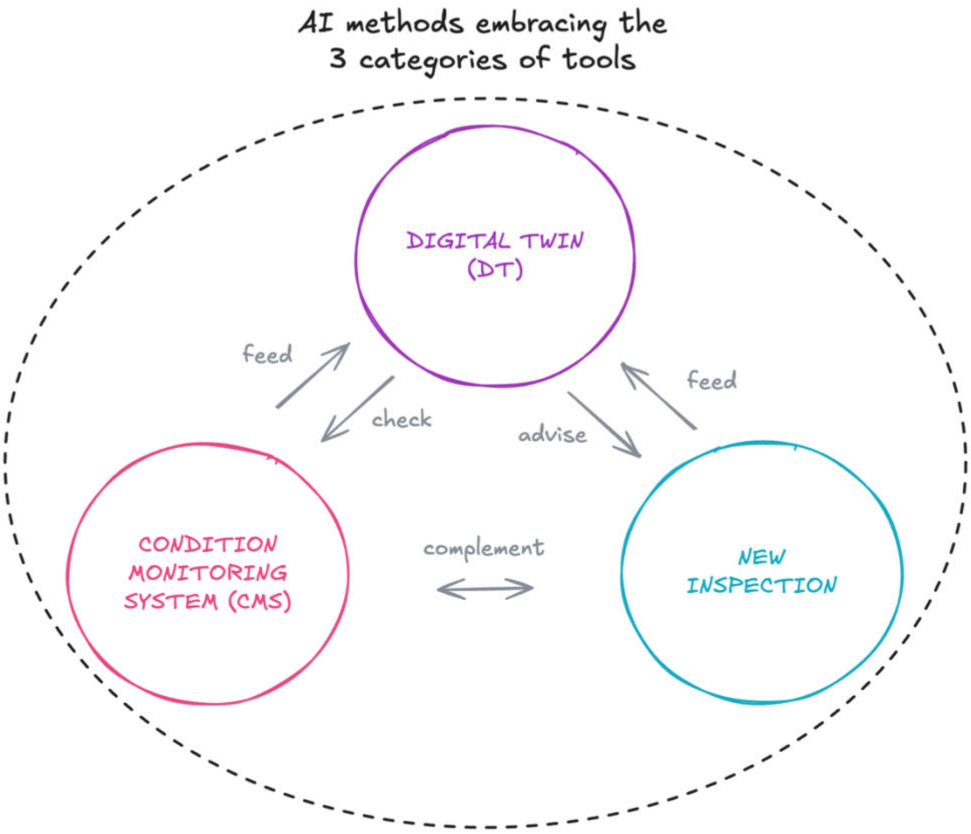

Figure 2. Three categories of digital tools for floating wind O&M. Source: PEAK Wind & WFO

New data analysis methods involving artificial intelligence (AI) can enhance the utility of all three categories. Regarding digital twins, AI can be used for surrogate models and synthetic data to address the limitations of numerical physics-based models (especially for data availability and computing power). Regarding CMS and inspection, AI can be used for the collection, post-processing and display of data to more safely and efficiently evaluate asset condition, detect anomalies, and calculate remaining useful life.

The first, most immediate benefit of digitalising floating offshore wind O&M is improving the visibility and management of the wind farm (broken down in Figure 3). An enhanced understanding of the asset condition guides maintenance decisions[2] which leads to OPEX

[1] Alternative wordings: advanced *or* comprehensive inspection, monitoring and maintenance strategy

[2] If maintenance is conducted prior to a failure, it is considered "preventive". Any maintenance activity following a failure is considered "corrective". The good practice in offshore wind is to conduct the vast majority of maintenance in a preventive manner. Preventive maintenance guided by real-time monitoring is sometimes called condition-based or "predictive" maintenance. The right maintenance strategy is, among other things, to be chosen based on the risk profile (probability and consequence of failure), the failure pattern and the detectability of the failure. Source: PEAK Wind

gains. The second, later-stage, benefit is that all the information being collected on the physical FOWT(s) contributes to a growing database that can be used to update the numerical models used in design, thereby improving the next generation of designs, which is particularly critical at the early stages of an industry. This White Paper will focus on the first benefit.

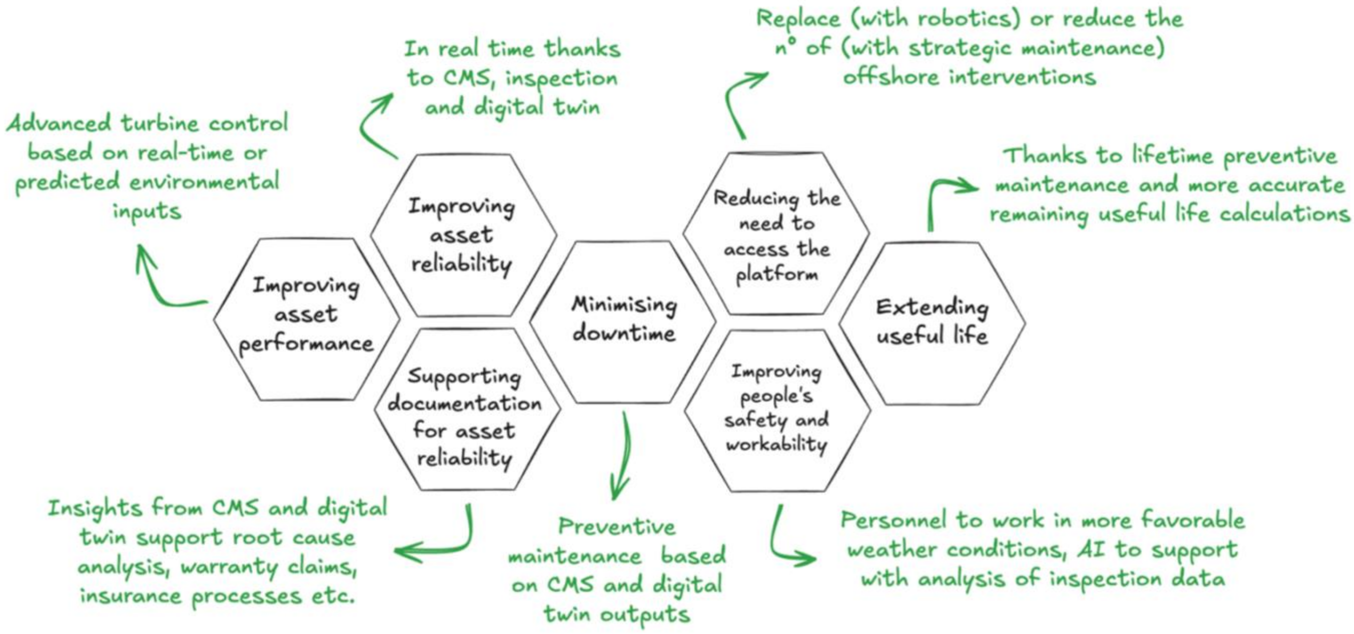

Figure 3. Seven ways to improve the O&M of floating offshore wind thanks to digitalisation. Source: PEAK Wind & WFO (adapted from FLOAT&M)

Both blue-collar and white-collar O&M work are improved thanks to the information provided by the digitalised O&M strategy. The safety and workability benefit to technicians are outlined in Figure 3 above, whereas the upside to non-technical areas are specified in 2.1 below.

2.1 Impact on Integrity Management

The offshore sector is concerned with safety, asset and environmental risks. The integrity management philosophy addresses these risks to ensure that the asset operates successfully in harsh weather and remote locations. The dual objective of integrity management is to minimise the risk of failure as well as downtime in the case of failure. For floating wind in particular, integrity management is crucial to de-risking the technology and improving its business case (e.g. by mitigating the consequences of a single mooring line failure, minimising lifetime costs for tow-to-port, supporting damage liabilities etc.).

Digitalisation is transforming the integrity management process as it is enhancing the understanding of the system's behaviour in real time compared to conventional methods.

1) **Augmented monitoring to improve the risk-based approach** and minimise the probability of unexpected failure

The integrity management process starts in the design phase. One of the first tasks consists of ranking the asset's failure modes and their criticality. This risk assessment then dictates the condition monitoring architecture (and possibly digital twin design) that will complement inspection and maintenance plans. The risk-based framework is combined with a prescribed approach, the latter often used to satisfy class/certification requirements.[3] The CMS and digital twin framework can help analyse and prioritise issues according to the risks and cost-benefit involved.

Long-term degradation threats like corrosion of chain, creep in synthetic mooring lines, water ingress of cables, marine growth, fatigue etc. have been historically difficult to track because of inexistent or unreliable sensors in subsea environments, or room for error and subjective judgment during inspections. Condition monitoring, inspection and advanced numerical techniques combined with AI will help consider many different parameters at the same time, solving the past decade's limitations to tracking complex, slow-moving phenomena.

Finally, there is a chance to *predict* asset behaviour based on validated digital twins that anticipate and quantify environmental stressors. With this knowledge on potential fault initiation and propagation, the operator can tune the system accordingly (e.g. WTG controller, active ballast as relevant) with a positive effect on the overall integrity and lifetime of the asset.

2) Data-driven inspection and maintenance triggers

Once the asset is in operation, real-time data from the CMS and digital twin provide the operator with unprecedented visibility into asset health and performance (= transparency of the numerical model). AI tools can automate the collection and analysis of large volumes of data to display on a user-friendly dashboard. Whereas alarms based on sensor thresholds are prone to false positives and negatives, the use of advanced[4] integrity key performance indicators (KPI) can help the user focus on the most relevant information. The operator can then make O&M decisions – e.g. further inspection, marine growth cleaning, maintenance campaign – in a way that reduces the risk of unexpected failure causing downtime or minimises the downtime if the failure cannot be avoided. A project that controls for business interruption is more likely to receive lower insurance premiums (= benefit of O&M strategy to insurance stakeholder).

3) Accurate life-extension analysis

The improved, real-time understanding of structural reliability will help quantify the locally experienced conditions per component for a more accurate fatigue consumption and remaining useful life calculation. Predicting the lifetime of the asset with greater level of detail has enormous economic impact on lifetime extension and asset valuation in investment/divestment transactions (= benefit of digitalised O&M to financial stakeholder).

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[3] Players in the oil & gas field have been transitioning from strictly prescribed to more risk based. O&M Subcommittee May 2024, WFO Moorings White Paper 2021

[4] Based not only on pure data analysis but correlation and detailed engineering analysis, e.g. not looking at the stress from a strain gauge as the KPI but rather the elaboration of a fatigue or remaining useful life coefficient based on the output of multiple sensors as the KPI

4) Plans for unexpected failures

While unexpected failures remain a threat for which maintenance will always be reactive, digitalisation enables vision on anomalies that can hint at issues that would otherwise go unnoticed. Should an unexpected failure occur, the enhanced CMS can better support root cause analysis, a very important source of information for warranty claims and liability allocation (= benefit of digitalised O&M to legal stakeholder).

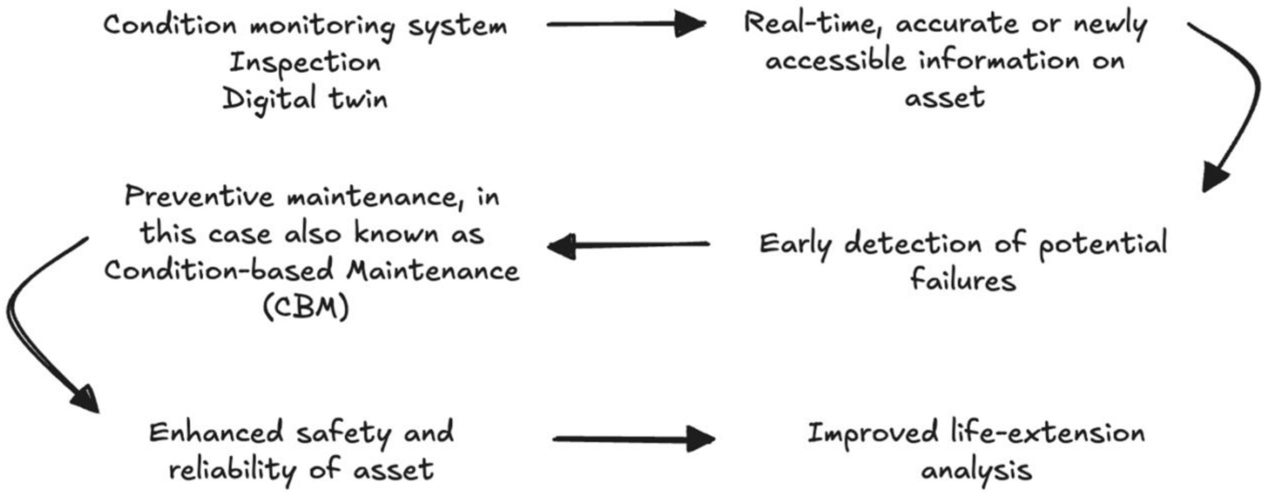

Figure 4. Simplified sequence of digitalisation's improvement to floating wind O&M. Source: PEAK Wind & WFO

3 Condition Monitoring, Inspection and Digital Twins

3.1 Condition Monitoring System (CMS)

The marine environment and real state of the FOWT often deviate from predetermined design conditions,[5] especially in this pre-commercial phase of the industry where there is still room for design and engineering optimisation. As such, a condition monitoring system (CMS) is put in place to monitor environmental conditions as well as the structural health and performance of the various components, among other aspects.[6]

The CMS consists of hardware and software (sensors and data acquisition feeds) that connect the FOWT or wind farm to a digital environment in order to detect and visualise changes that could indicate a developing fault. Its exact architecture varies per project. Sensors can either be hardwired (physically connected to a network via wiring) or standalone (operate independently and typically require batteries). Both types have their pros and cons on aspects like compatibility, cost, placement, reliability, durability, data quality and availability.

Typically, the WTG has a standard CMS given track record in onshore and bottom-fixed offshore wind. The data of the WTG sensors is brought together in the SCADA (supervisory control and data acquisition) system. The rest of the FOWT (floater and subsea components) is where there is no standardised monitoring approach, let alone standardised substructure designs. Right now, research & development is still looking into what combination of CMS for the various components enables the right holistic view of the FOWT in terms of cost and long-term utility.[7] New floating wind components would ideally be designed with a monitoring solution in mind to maintain competitiveness, for example dynamic cable buoys or mooring line load reduction devices with built-in sensors.[8] Some underwater sensors have track record from the oil & gas fields but may be more costly to install and maintain in floating wind.

On the contractual side, the turbine OEMs might provide a consolidated set of sensors along with the WTG as part of the Turbine-Supply Agreement. The agreement conditions vary per project, with some widening the sensor scope to include foundation or additional instrumentation. Similarly, the agreement outlines which data is made available to the project. Since the scope in floating wind also includes the floating foundation, mooring system and cable, currently few stakeholders are capable of supporting an integrated package alone. Projects will therefore have to undergo a collaborative exercise full of interface issues – technical, contractual and logistical – until a more unified, streamlined approach emerges.

Security[9] and intellectual property (IP) issues further complicate an integrated condition monitoring system. For example, while a direct link between sensors on the floater and the

[5] Liu et al. 2023 in *A digital twin-based framework for simulation and monitoring analysis of floating wind turbine structures*

[6] Structural health monitoring (SHM) is one aspect of the wider condition monitoring system (CMS)

[7] Most academic research cited in this paper reflects this. Example research projects tackling a wind farm approach: FLOAT&M (2021-2023), Carbon Trust CMIM (2022-2025)

[8] TFI Marine presented on the monitoring solution for its load reduction device at Floating Wind Aberdeen 2024

[9] It is worth noting the broader discussion on cybersecurity for digitalised power and information systems in relation to privacy, national security and geopolitics. Regulation on AI like in the EU will impact the extent to which some technologies can be used

WTG controller would augment the latter's response, it is not standard practice.[10] Instead, third-party solution providers have to develop the sensor and the data transmission tools in parallel to the existing turbine sensor set-up which creates inefficiency on data handling and interpretation, thus raising costs.[11]

One other big gap in wind energy condition monitoring is in the quantification of wind fields in and around wind farms. Remote sensing (lidar, sodar, radar) and mobile sensor technologies are emerging but need to prove their benefits to be integrated into projects.[12]

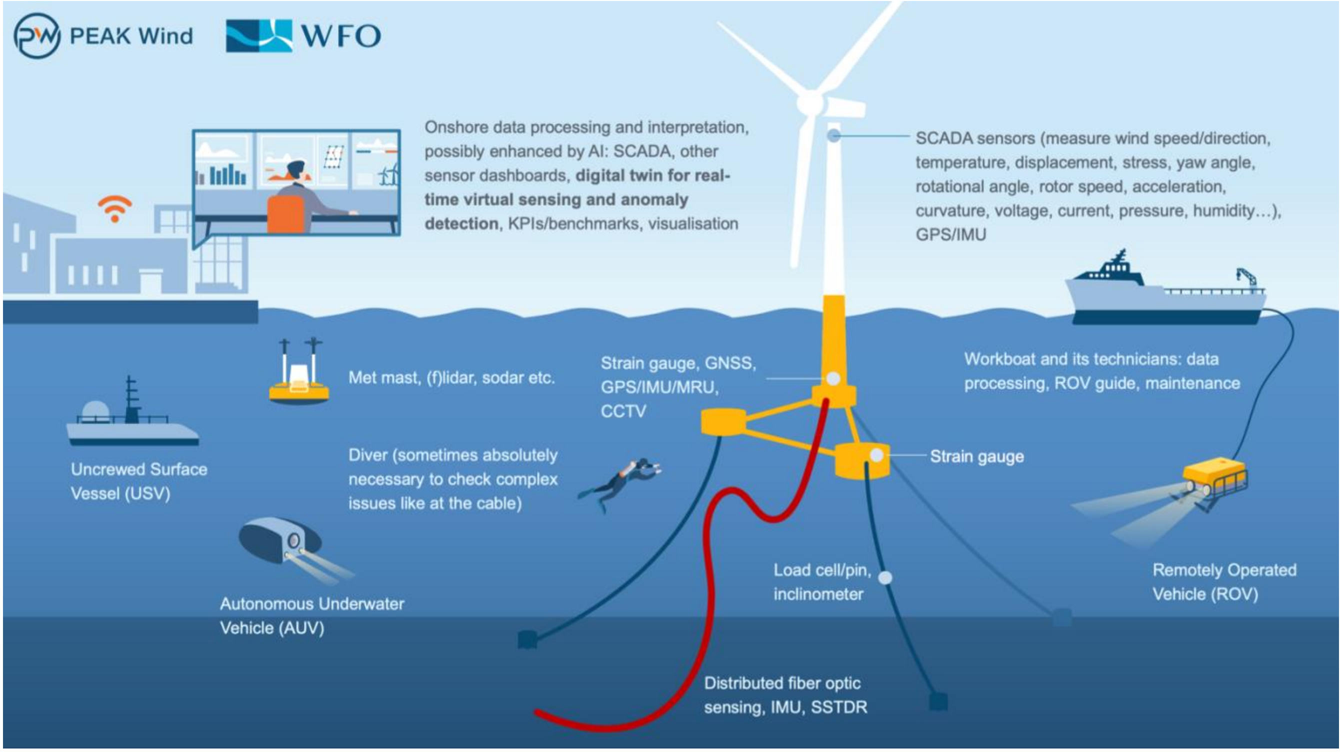

Figure 5. Master figure of the typical sensors, inspection methods used on a FOWT. A project would not necessarily use all of the equipment pictured; the final choice depends on the project conditions. Even if many of these technologies are already adopted today, they are still not utilised at their full potential in a centralised integration. Remaining acronyms elaborated at the start of the paper. Source: PEAK Wind & WFO

[10] One operational floating wind demonstrator benefits from a link between the sensors on the floater and the WTG control system because of the unique way in which the operator acquired the turbine for its project. It is otherwise uncommon. WindEurope Bilbao 2024 O&M in Floating Offshore Wind Workshop

[11] To address this overarching challenge in wind energy (onshore and offshore), Clifton et al. 2023 in *Grand challenges in the digitalisation of wind energy* recommend planning for a high-bandwidth open network with strong security implemented at the hardware level

[12] For example, the Carbon Trust has been working to accelerate the acceptance of floating lidar to replace meteorological met-masts for the measurement of primary wind resource data (wind speed and wind direction)

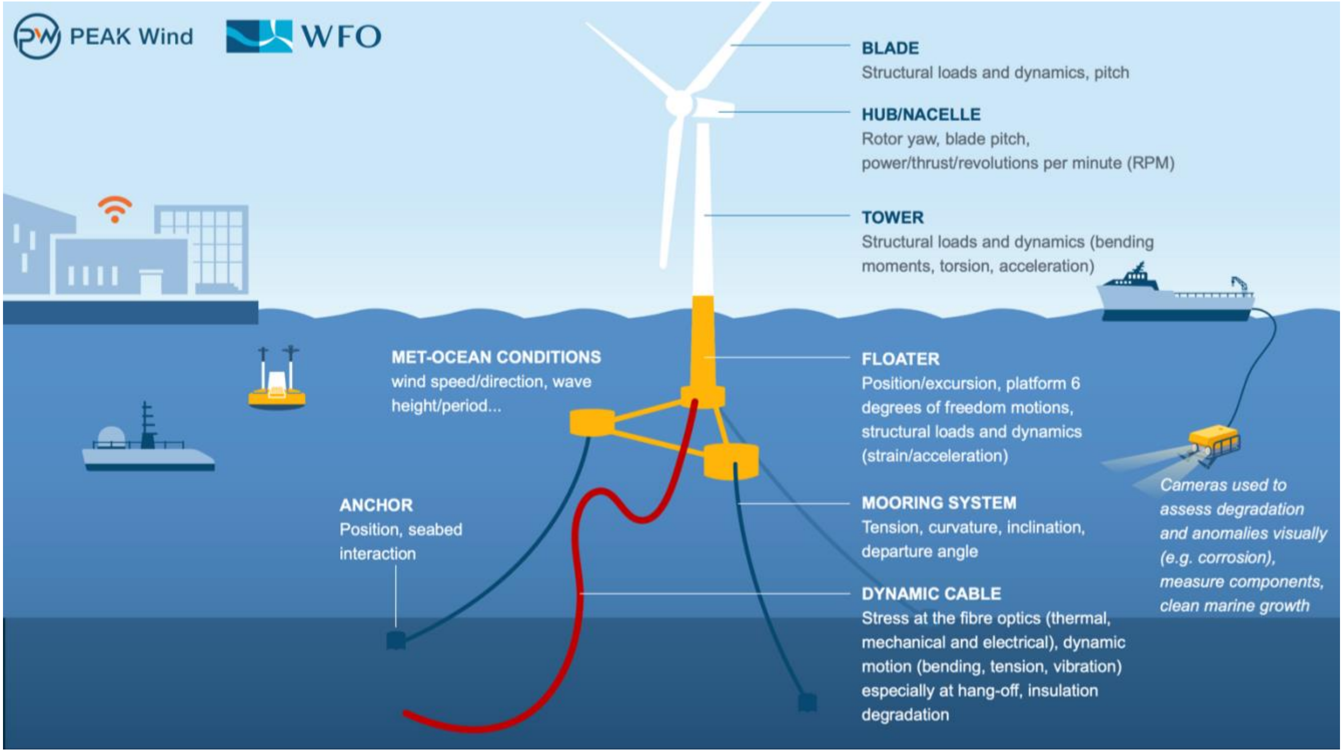

Figure 6. Summary of the information typically sought after in FOWT inspection and condition monitoring Source: PEAK Wind & WFO

3.2 Inspection

Visual inspection is an important part of the integrity management plan as it is first used to obtain a baseline profile of the system once it is installed (also known as the as-built inspection). The as-built inspection is typically a contractual obligation to the installation company to make sure that the latter installed the asset without any damages/within the tolerances. All the observations (qualitative) and measurements (quantitative) serve as a reference for future monitoring, inspection and maintenance activities. Inspections describe parameters like position, thickness, deformation, cracks, marine growth etc. Over the life of the wind farm, the as-built baseline is compared with ongoing CMS data. Poorly documented as-built inspections create gaps in the baseline, later on impairing the capability of certain sensors to provide trusted values or the operator to implement drift corrections. Throughout the rest of the wind farm's life, inspections are scheduled as part of the integrity management programme.

Robotics (Remotely Operated Vehicles or ROVs) have been removing the need for divers to perform most visual inspections. ROVs are supported by a crewed vessel for power and control. Technology and cost improvements of ROVs are making them compatible with floating wind maintenance. More forward-looking technology can remove the need for a support vessel altogether. This is the case of Autonomous Underwater Vehicles (AUVs) or Uncrewed Service Vessels (USVs) which are both in early development.[13] Possible powering is

[13] Examples: Fugro completes world's first fully remote offshore wind ROV inspection in 2023 using a USV; HonuWorx's world first demonstration of AUV in 2023

by batteries, hydrogen fuel cells, solar energy or subsea docking stations. Internet connection helps supervise and control the vehicles from the shore. Above the waterline, drones are revolutionsing WTG inspections by replacing the need for a technician to climb the structure.[14] It is expected that inspections carried out by new robotics or other[15] will first adopt a qualitative role before gradually taking over the quantitative measuring and maintenance activities normally performed by known methods.

Lastly, artificial intelligence in inspection activities can free personnel from the tedious task of evaluating hours of footage/measurements on a given component. Vision models are trained to parse through the data and flag anomalies faster. Personnel can intervene in a second step to confirm the analysis.

3.3 Digital Twin (DT) for floating wind O&M

3.3.1 Definition, model design and purpose

In simplified terms, a digital twin is a virtual representation (= model) of a real-world FOWT, its individual components and environment. The real-world FOWT and the virtual representation are linked by data: from the physical asset to the virtual representation and in some cases the inverse. The FOWT's structural characteristics from design as well as its condition monitoring and inspection data from real operations feed the digital twin (= inputs). The digital twin uses this data and computational models that are either physics-based or AI-based to calculate system states, i.e. inform on the asset's current (and sometimes future) condition in real time or near-real time (= outputs). These outputs can contribute to more or less advanced KPIs (technical or commercial) that help the user understand the asset condition and make maintenance decisions throughout its life. The digital twin only transfers information back to the physical asset for closed-loop actions like the WTG control system. Big data methods are needed to store, process, analyse and transmit all the data on the asset. Managing uncertainties across the digital twin's development is crucial so that the outputs continuously support the integrity management of the FOWT or wind farm.

[14] Business Norway article about using drones for offshore wind turbine turbine inspection

[15] Photogrammetry, SLAM (Simultaneous Localisation and Mapping) and thermal imaging were discussed in the various Subcommittees for inspecting moorings and cable components. One Horizon EU project looked at using a hyperspectral camera to detect early marine growth on ship hulls

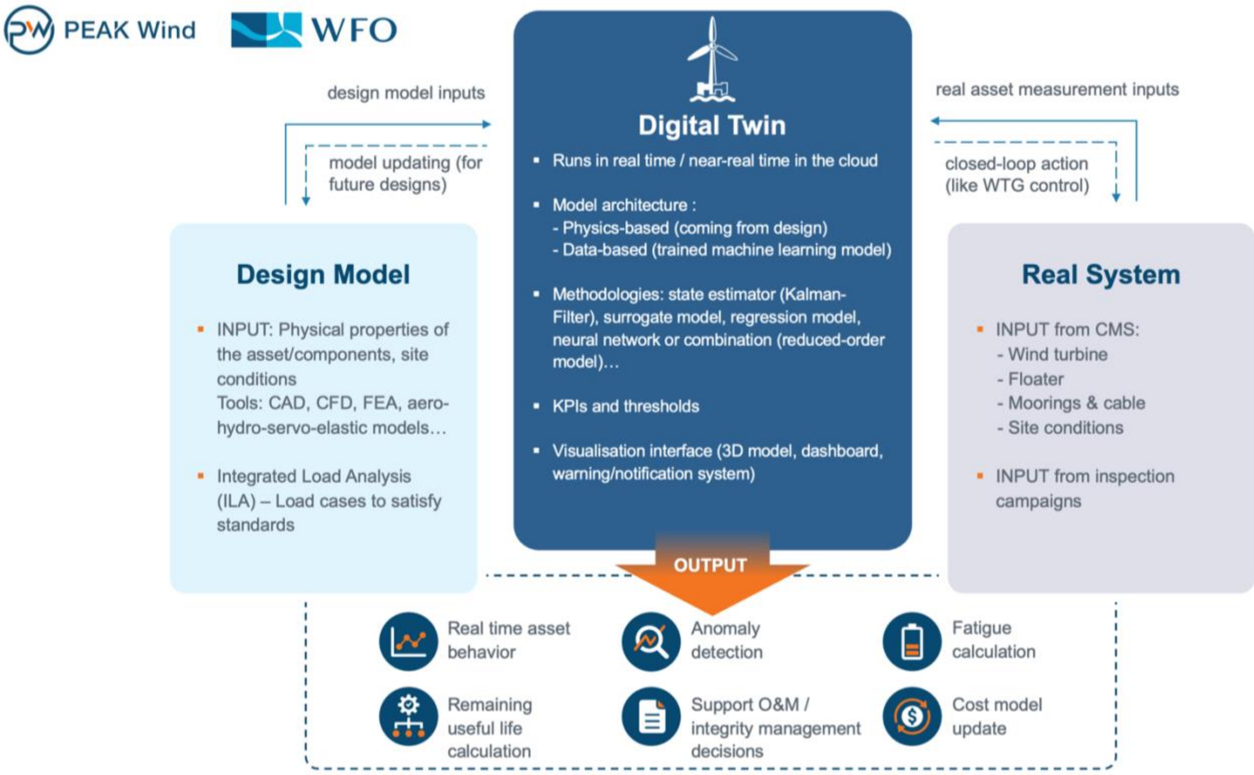

Figure 7. The digital twin concept. Source: PEAK Wind & WFO

Digital twins use design and monitoring inputs to output the asset condition in real time. The model itself is developed in two main ways described below.[16] The physics-based approach relies on an understanding of the physics behind the FOWT interactions and responses. The data-based approach skips the underlying physics and only requires a dataset with inputs and outputs. Within physics-based and data-based methods, there are different modelling approaches.

- **Physics-based Models**
    - Use physical equations to represent the behaviour of different bodies and their mutual interaction (e.g. multi-body / finite element method model)
    - Provides phase-resolved time series with states and parameters that have clear physical meanings (white-box models)
    - **Strength**: High transparency, no training data needed, very flexible in adjusting to changed system parameters
    - **Drawback:** Requires a suitable model that represents the physics of the system and is suitable for a state estimator. Additional uncertainty between model parameters and as-built structural properties

- **Data-based[17] Models**
    - Typically use regression methods or neural networks to map inputs to outputs
    - Neural networks require a lot of data to train the model to map the input-output relationship. Generated or synthetic data is helpful when training data is limited or the

[16] O&M Subcommittee November 2024
[17] Alternatively named Data-driven, Machine Learning, AI Models

physics are too complex to be worth modelling. The synthetic inputs need to be consistent with the expected behavior and statistical properties of their real alternatives

- Work with statistical methods and are considered black-box models, meaning that the internal states lack physical meaning or interpretability (the user only knows the inputs and outputs)
- **Strength:** Effective for pattern recognition and predictions
- **Drawback**: Limited transparency from lack of physical input-output meaning. High effort to create training data base, limited flexibility to adjust to changed system properties due to need for retraining of model

Once operational, the digital twin can specifically provide a project with:

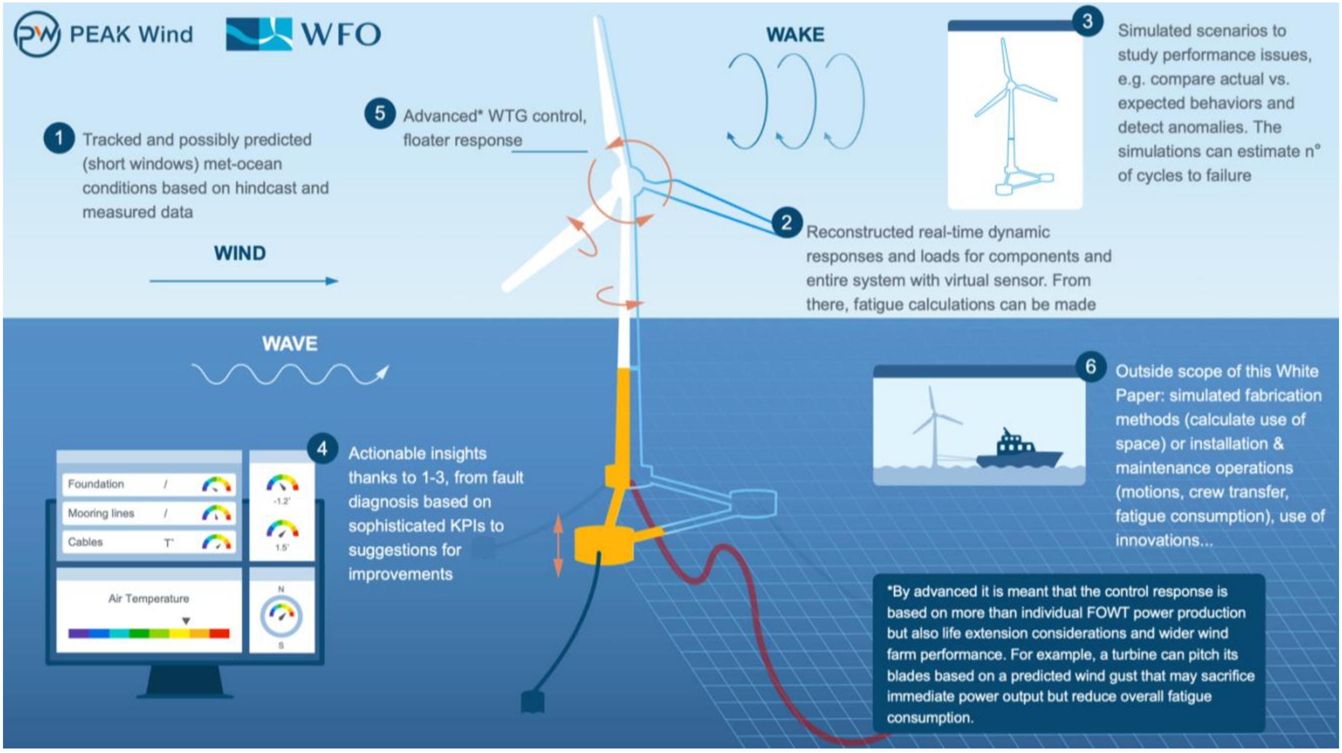

Figure 8. Main applications of a floating wind O&M digital twin.[18] *Source: PEAK Wind & WFO*

In the above figure, points 1, 2 and 5 are strictly in real time or in-the-loop. Points 3, 4 and 6 can be occur in near-real time or offline.

Point 2 refers to the concept of the virtual sensor, a crucial benefit of the digital twin already used in the defense and aerospace fields. According to the International Electrotechnical Commission, virtual sensors are software-based models of physical sensors that can simulate their behavior and generate sensor readings without the need for actual physical hardware. In other words, they are digital twins that can estimate parameters not directly monitored by real life sensors. With virtual sensors, a fuller picture of the system can be captured at a lower cost.

[18] Example for point 6: digital twin and AI will be used to assess the workability of a proposed SOV concept for floating offshore wind by North Star, focusing on vessel motions, gangway performance, and movement range of the floater

Point 3 on anomaly detection is another important function of the operational digital twin. Simulated performance responses (structural integrity, dynamic behaviour, operational efficiency) are compared with observed behaviour informed by the CMS and inspection data. Differences between expected and observed states are flagged which can then prompt further investigation or maintenance. Anomaly detection is dependent on the thresholds set by the digital twin creator and his or her knowledge of the component/asset, failure modes and level of conservatism. If training an algorithm for anomaly detection, it must also understand the context of the data it is analysing to avoid signaling false positives. The cost of responding to false positives can be substantial, and on the other hand a missed anomaly can have severe consequences.[19]

3.3.2 Development of the digital twin as part of a holistic approach

The design phase should be the starting point for the digital twin development. The models and simulations utilised for design are the building blocks. In this period, the digital twin under development is of a non-existent asset and so it is termed a "prototype" digital twin.[20] In parallel, the CMS architecture and inspection method/schedule are conceptualised.

Figure 9. Example of full integration of the digitalised O&M strategy in project workflow. Source: PEAK Wind & WFO

Model simplifications are required to capture the complex aero-hydro-servo-elastic dynamics of floating wind systems. For digital twins, modelling tools are selected per component and design stage based on their ability to represent specific phenomena, speed (computational power), accuracy and accessibility. On a case-by-case basis, a clever combination of physics-

[19] Stadtmann and Rasheed 2024 underline the importance of contextualising certain data points to prevent their model from signaling false positives

[20] Digital twins roundtable at WindEurope Annual Event, Copenhagen 2025: It is possible for prototype digital twins to remain as such if their utility is purely to test/visualise/rehearse phenomena such as complex and/or innovative scenarios say in fabrication and installation

based and AI-based methods are selected to obtain both high accuracy and fast computation.[21] Reduced-order models or surrogate models can be used to work within computational power limitations, both with and without AI.[22] Verification with known modelling approaches and scaled wind tunnel and tank testing help confirm that the digital twin model is accurate.[23]

Once the digital twin is linked to the physical, operating asset, a validation phase to finetune the model parameters is done with the physical asset's first measurements. A continuous validation loop is important to ensure that the digital twin always reflects the asset's real condition which evolves over time. AI can help make this process more efficient and reduce manual maintenance of the model.

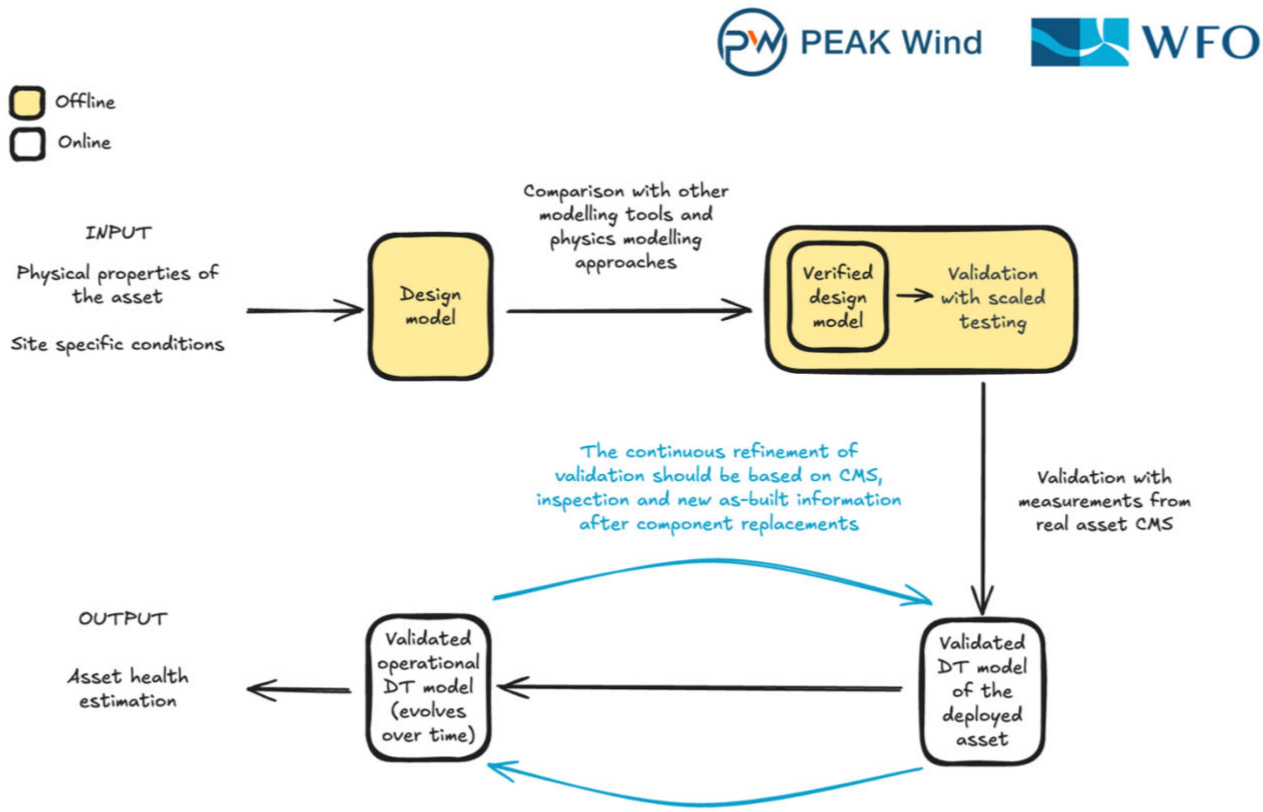

Figure 10. Digital twin development main activities. Source: PEAK Wind & WFO

Throughout the lifetime of the wind farm, the modelling framework is continuously updated by the CMS and fills in the gaps for areas on the asset where there is no sensor to get a global overview (= virtual sensor).[24]

[21] O&M Subcommittee July 2024, May 2021

[22] Ludot et al. 2025 presents a methodology to develop machine learning-based surrogate models designed to predict, in real time, hourly fatigue damage accumulation in the catenary chain mooring lines of floating wind turbines

[23] Scaled physical testing is technically a first validation exercise. Although, Gueydon et al. 2020 state that "to continue improving scaled testing techniques, there is an acute need for more comparisons between different testing approaches and validation against full-scale measurement campaigns."

[24] Browsing the literature on offshore wind / floating wind digital twins will show a wide variety of virtual sensor applications

3.3.3 Managing uncertainty

A digital twin is only as good as the data and physical knowledge it has as inputs as well as the accuracy of its references for model verification/validation. Uncertainties throughout the model's development can cumulate into an incorrect digital twin representation of the FOWT or wind farm. Four uncertainty areas are identified in Figure 11 with Table 1 detailing their significance and possible mitigation measures.

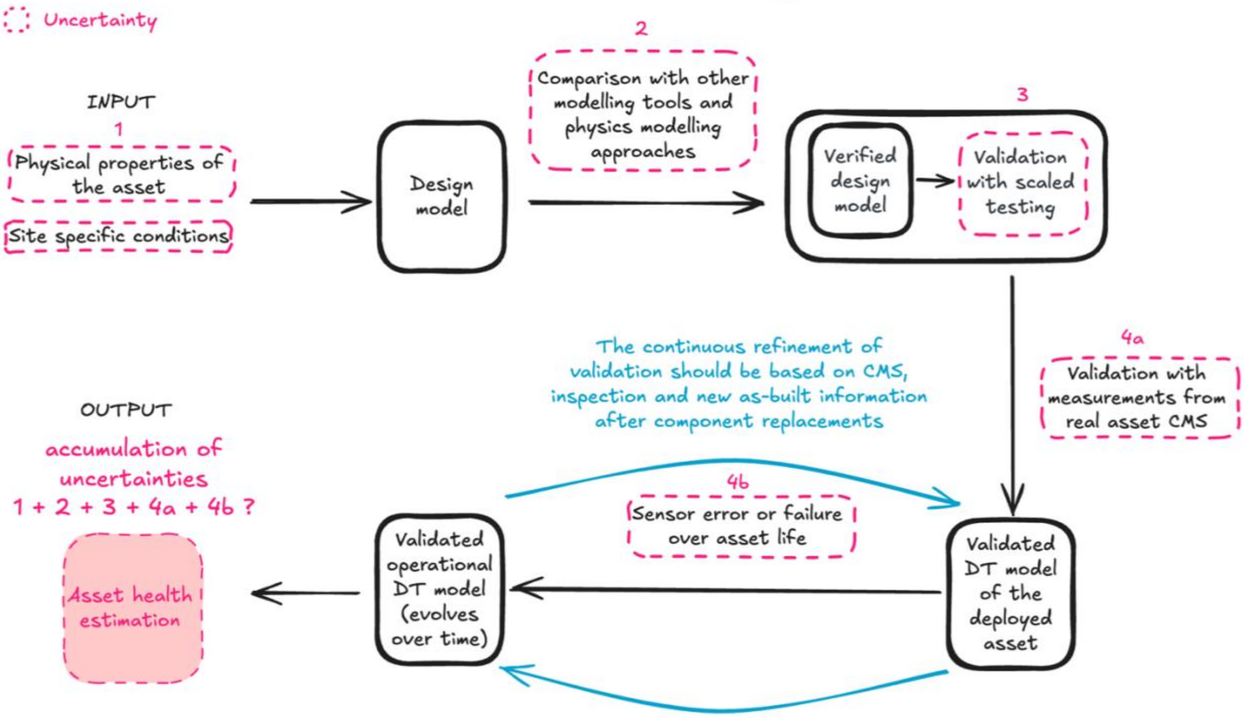

Figure 11. Accumulation and propagation of uncertainties in digital twin development from Figure 10

Table 1. Breakdown of uncertainties and their mitigations. Source: PEAK Wind & WFO

	ACTIVITY	UNCERTAINTY	ISSUE	MITIGATION
1	Input physical properties of the asset, site specific conditions	Availability (volume, format) and quality of data, for example wind/wave input Accessibility limitations to structural characteristics due to IP, security or technology not yet selected	The accuracy of the inputs is important for building a representative model and for defining appropriate threshold values for anomaly detection	Early consideration of digital twin concept within the project, collaboration between technology providers (including turbine OEM) to make structural inputs available Minimum time for metocean campaigns to be statistically significant Third-party models (e.g. WTG model from design house) or machine learning algorithms can be used to fill in the gaps for structural inputs
2	Verification: Comparison with other modeling tools	Direct comparability with other physics-based numerical approaches	Impact on ILA and detailed design	Third party verification for benchmarking
3	Validation: scaled test tank	Consistency of measurements at different scale	Replicating complex dynamics at a scaled level may not necessarily reflect true full-scale response	Different scale testing in the technology qualification phase, possibly not only lab but also at sea in controlled environment
4a,b	Validation: with measurements from physical asset	Accessibility limitations due to IP or security Inconsistency, missing, inaccurate or duplicate sensor data Other hardware malfunction/outage	Leads to underestimations Simply cannot validate digital twin model	Consideration for digital twin employer's requirements from the design phase of the project so data sharing set-ups are clear and in place Sensor built-in anomaly detection; statistical methods to fill in gaps for calibration errors or missing data; backup sensors or models relying on subset of data streams to counter sensor outages; data recovery State estimators like a Kalman-Filter to find the state of an asset (e.g. motion, velocity and acceleration) given input data and/or model uncertainty. Includes ability to adjust to quality of available sensor data throughout wind farm life (= redundancy) Inspection checks to corroborate outputs
Σ	Output prediction of asset behavior, information for asset management	Cumulation of uncertainties throughout the digital twin development timeline	Multiple layers of uncertainty propagation thus reducing the added value of the outputs	

3.3.4 Digital twin applications & capabilities

A lot of information is generated from digital twins, and so it is possible to classify them according to their application (from individual component to sub-system to whole system) and capability.[25] Digital twins are more complex with increasing scale of application and/or capability level.

1. **Descriptive** – describes system design and current situation
2. **Diagnostic** – identifies why and how failures occurred
3. **Predictive** – anticipates when the system might fail by quantifying existing and future stressors and estimating their effects on the current condition and remaining useful life
4. **Prescriptive** – Combines former with uncertainty quantifications, what-if analyses and risk estimations to recommend actions when failure is imminent
5. **Automated** – implements automated solutions for performance improvement, condition monitoring, integrity management (closing the loop)

Industry developments are targeting predictive and prescriptive support for floating wind farms. The real-time nature of the model is the novelty compared to classic condition monitoring. Digital twins of

[25] O&M Subcommittee October 2023 and April 2024 discussed the capability levels, but they are also presented in literature, for example in Stadtmann et al. 2023 (see References)

levels 4-5 directly contribute to asset management activities. Digital twins of levels 1-3 can be used for load case simulations, failure root cause analyses or other tasks that do necessarily require real-time inputs.

3.3.5 State of digital twin development today

Today's digital twins are diagnostic in nature, using current and past asset information for anomaly detection and fatigue-life estimation of specific components rather than a larger sub-system or whole system. The use of AI tools for digital twins have seen significant improvement. Existing works typically rely on standard, easily available turbine measurements like from the SCADA system and/or additional sensors. A sub-set of the literature incorporate communication/visualisation tools (text message, alarms, 3D models, virtual reality etc.) to enhance the digital twin's user interface.[26] The studies exhibit overall positive conclusions but they acknowledge their limitations regarding scope (single component), data availability (insufficient), and assumptions (which may have been simplistic).

Only a few studies have been able to validate against selected datasets of operational FOWTs (which was provided under agreement or publicly available).[27] These works have revealed a gap between the existing CMS data and the ideal information needed to support digital twins. For example, two digital twin exercises using the same dataset of an operational project noted failure to validate their models because of the following issues: lack of certain data, spurious transitions in data, noise[28] – all issues pertaining to section 3.3.3. on uncertainties above. Two other studies on separate demonstration units explained how they were able to work with the available project data.[29]

While digital twin development should guide the CMS architecture of the FOWT/wind farm, here we see digital twins being conceptualised post project commissioning with their purpose sometimes influenced by what operational data is available to use. Nevertheless, these exercises are guiding the monitoring specifications necessary to allow for a digital twin. Eventually, full integration of digital twin into the project workflow will help validate their full potential.

Funded research at the country or regional level are connecting solution providers to pilot and pre-commercial opportunities to continue validating digital tools and simply practice the integration of a holistic CMS and inspection plan.[30] On a private level (initiative by the project

[26] Such as BIM (Building Information Model) visualiser, video game engines, virtual reality etc. Examples: Moffatt & Nichol on offshore wind port planning at WindEurope Annual Event Copenhagen 2025; Stadtmann & Rasheed 2024; Zhang & Zhao 2023; Ciuriuc et al. 2022; Kandemir et al. 2022

[27] For example: Branlard et al. 2024 (TetraSpar), Stadtmann & Rasheed 2024 (Zefyros/Hywind Demo), Walker et al. 2021 (Hywind Scotland). Other studies validate their digital twins against other simulation tools

[28] O&M Subcommittee April 2024, Moorings Subcommittee July 2021

[29] Stadtmann & Rasheed 2024 explain how their methodology for anomaly detection was in part guided by the available project data frequency. Branlard et al. 2024 recommend placing additional accelerometers or load cells along the tower to improve tower load estimation via their digital twin

[30] Past/ongoing/future projects presented on or alluded to within the O&M Subcommittee: ARPA-E 2019 funded by the US Government to support a digital twin on the WindFloat Atlantic project; FLOAT&M 2021-2023 funded by the European Regional Development Fund and the Basque Government where one work package focuses on a digital twin; BLOW 2024 funded by the EU Commission to develop a floating wind demonstrator in the Black Sea – a digital twin to analyse the interaction of the FOWT and power grid will be created. There are many other similar exercises, both private sector-led or university-led, that use unique combinations of models and data that they have access to. In the 2023 paper *Grand challenges in the digitalisation of wind energy*, the authors support using pilot projects to validate the benefits of digitalisation

shareholder/operator), the TetraSpar Innovation Challenge has six out of eight companies testing digital twin, monitoring and/or forecasting solutions on the TetraSpar demonstrator.[31] Full-scale met-ocean, structural, motion and position measurements as well as turbine SCADA information are provided to the winners. In addition, there is access to numerical models, tank test data and assembly & installation data.

3.4 Vision for commerical scale monitoring approach

As opposed to in oil & gas where a single asset is heavily instrumented, floating wind needs to monitor dozens of assets and at the same time satisfy project economics. However, instrumenting several FOWTs with the same CMS is not only costly but also very demanding in terms of maintenance. By developing a digital twin, there is a chance to use the CMS more wisely, meaning using less but also specific hardware to track the performance of all FOWTs. Clustering is a concept that instruments one to a few turbines representing a larger cluster. The data coming out of the heavily instrumented turbine(s) is then used to simulate the performance of the less instrumented turbines of a same cluster.[32]

The clustering approach is part of the integrity management process for the wind farm. For example, in the case of mooring lines, over-instrumented unit(s) can be chosen per water depth, prevailing wind/wave conditions and modelled wake distribution.[33] An alignment of prevailing wind and wave conditions simplifies the overall exercise. More complex, multi-directional site conditions require a holistic optimisation approach.

[31] Four of those six companies presented within the O&M Subcommittee and Moorings Subcommittee between 2021-2024
[32] Agreement to this approach was echoed across all O&M Subcommittee meetings. Blog articles about this topic and other studies also speak of the clustering approach as the solution to + 250 MW floating wind farm management
[33] This was the focus of The Carbon Trust Commercial Scale Mooring Integrity Management (CMIM) project. Partners developed a mooring integrity management strategy for a floating wind commercial array. The clustering approach is an integral part of the strategy

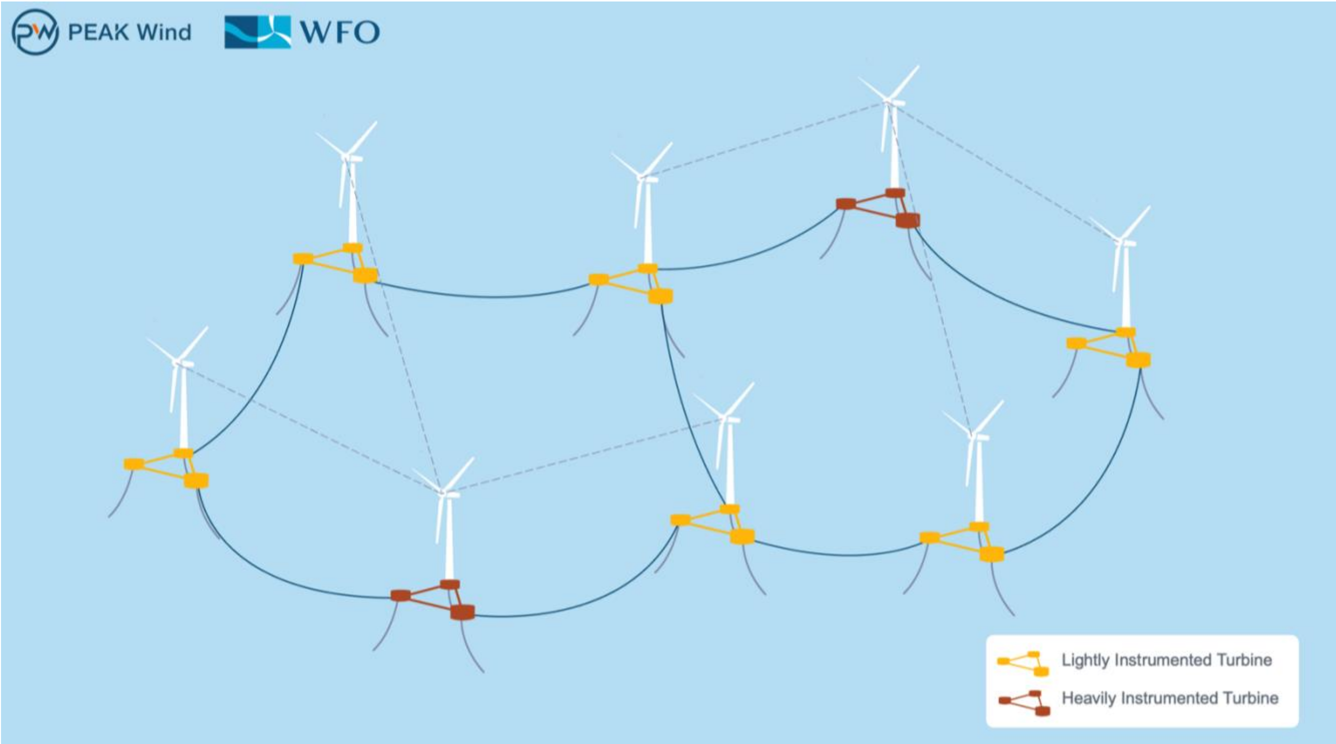

Figure 12. Illustration of the clustering approach. Every turbine is to contain a standard set of sensors for motion and positioning that are relatively cheap and easy to install (see Figure 5). Data from the heavily instrumented sensors are used to extrapolate via models the performance of non-instrumented turbines (represented via dotted line). Source: PEAK Wind & WFO (adapted from Ozea)

Regarding the selection of hardware, the virtual sensing feature of the digital twin allows the project to invest only in sensors that are easier to install and maintain (e.g. above the waterline). Despite their location, these sensors can estimate responses at key points subsea. Taking the example of a mooring line, a digital twin uses readily available positioning data (e.g. GPS and MRU) from sensors at the hull[34] to reverse engineer the line's tension (and from there fatigue consumption).

Even with the selection of fewer units to monitor heavily, floating wind farms will require the processing of massive amounts of operational data quickly and securely, hence the need for big data methods. The future of floating wind digital twins will also involve the integration of models from design and construction to installation and O&M. Life-cycle products that allow such a transition between phases are under development in both the private and academic spheres.[35]

[34] As opposed to a load cell along the mooring line (subsea) which can measure tension and inclination but is costly to install and not as reliable. O&M Subcommittee April 2023, July 2024, November 2024

[35] For example, the Cables & Floating Substations Subcommittee June 2025 meeting mentioned the need for "cable fingerprints" that span testing, manufacturing, storage, installation and operation. However, the O&M Subcommittee December 2023 highlighted the challenge in creating a data platform that seamlessly links the design phase to the operational phase. Liu et al. 2023 state that monitoring and simulation technology in installation and O&M are often researched independently and so they propose a unified framework to model a floater design from installation into O&M

Figure 13. Favorable characteristics of a digital twin. Source: PEAK Wind & WFO

4 Business Landscape

The business case for digitalising floating wind O&M is not yet standard practice because of:

1) Low track record for integrating a comprehensive CMS and digital twin
2) Fragmented supply chain with many providers focused on sub-sets of the wider picture
3) Transparency limitations which slow adoption of technology
4) Unclear cost-benefit analysis of digitalised O&M scenarios versus business-as-usual
5) Recommendation rather than prescription by classification societies for segments of the digitalised O&M strategy

4.1 Low track record of a comprehensive CMS and digital twin

While turbine monitoring is already well embedded in the wind project workflow thanks to onshore and bottom-fixed wind experience, the rest of the floating wind system (station-keeping and cable) is lacking. As portrayed in Figure 5, there is a large catalogue of monitoring and inspection tools for the floater and subsea components (plus associated modelling techniques) that need further development and track record in a *comprehensive* deployment. Across the whole wind energy industry, there is also a gap in considering the wider wind farm on top of individual turbine performance which could help with managing spatiotemporal flow, life extension, or energy market fluctuations.

No project has yet executed a comprehensive digitalised O&M strategy. Indeed, the digital twins being validated on pilot projects today are add-ons to the monitoring framework previously put in place. Their purpose is mainly to validate the substructure numerical models and improve future design iterations. Insurers and financers acknowledge the potential of digitalisation for O&M[36] but struggle to see the utility if not yet appropriately integrated into the project.

Developers need to adopt a forward-looking view to integrate a digitalised O&M strategy from the start of their projects. This suggests a different pathway from oil & gas, where technical and economic risk assessments have led to a focus on equipment redundancy (like multiple mooring lines) over advanced condition monitoring with digital twins. The nature of an oil & gas platform as a single asset with large margins justifies the CAPEX costs associated with equipment redundancy. The risk profile for floating offshore wind is different: building dozens of turbines with smaller margins limits room for the CAPEX. In this case, an advanced monitoring approach is expected to provide greater marginal upside.

[36] The JNRC Risk Engineering Guidelines for the Insurance of Floating Wind Farms cite CMS and digital twins as key tools to mitigate technology concerns across components. Banks are aware of these solutions to tackle O&M risks (Interface Risk Subcommittee May 2025). Beyond O&M, digital twins can improve the transparency of the asset's state for final valuation

4.2 Fragmented supply chain with many providers focused on sub-sets of the wider picture

The immaturity of the digitalised O&M strategy contributes to an unclear supply and demand of related technologies. At the moment, there is a large diversity of suppliers with niche specialisations in CMS equipment, digital twin software, packaged product/service, prior wind energy or oil & gas track record, joint industry project/academic experience etc. They come with varying degrees of go-to-market maturity to support projects. This fragmentation of expertise complicates the full integration of information between components for a holistic monitoring system.

The main users of the CMS and digital twin are the developer, operator and asset owner. Each is interested in different information that the system provides. The developer seeks to design a robust yet cost-effective and code-compliant, de-risked monitoring solution that is also suitable for insurers and financiers. Operators are the ones using the system and their focus is on managing it according to wind farm KPIs. Finally, the asset owner's interest mainly lies in how the system increases profitability. One organisation can act on behalf of multiple user types. To maximise the addressable market, providers offer scalable and tailorable services. They are willing to retrofit their core offering for their clients (e.g. tailoring data to operator dashboards).[37] Some providers are partnering up to offer a more comprehensive solution, which can be attractive to users that cannot master the digitalised O&M strategy on their own.[38]

At least for the upcoming floating wind projects, it is generally understood that early engagement by providers – in FEED or before – is crucial for an optimal O&M set-up because the developer can be made aware of the digital solutions available and design the project with their added value in mind. The more a project has to retrofit a digital twin and other condition monitoring technology to set hardware and software, the more expensive and less optimised the outcome becomes (compared to developing the digitalised O&M strategy right from the start). Figure 9 from earlier is an example of how a project should plan the digitalised strategy first, then design and procure the necessary equipment.

A clear bid call for a comprehensive CMS would allow the supply chain to organise itself for a given project. Regulation can support the developer's first mover risk, for instance through criteria for innovation in project tenders or direct financing of technology development and data-sharing forums. On the last point, data-sharing by OEMs can be challenging due to security, IP, competition or risk of liability. When data is provided, it has to be standardised in common formats and stored in secure systems.

The large-scale agreement between Microsoft and SBM Offshore is one example of the start of a major shift to integrate digitalisation in the offshore industry. The collaboration will

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[37] Thomas et al. 2025 *OTC-35690-MS Advancements in Offshore Mooring Monitoring: A Case Study on the Prelude FLNG* is an example of a successful retrofit of a new monitoring methodology into existing infrastructure with no new sensors or other hardware. For floating wind, providers in the Subcommittee have often mentioned that their models can be adaptable to a range of turbine and floater types as well as major maintenance campaigns like tow-to-port or on-site methods (O&M Subcommittee November 2024, April 2024, December 2023)

[38] Example of Ozea, joint offering by sowento and AMOG to provide holistic offshore and floating wind condition monitoring in commercial-scale wind farms by combining sowento's experience in wind turbine simulation/modelling and AMOG's experience in offshore mooring and subsea system monitoring

explore new ways to integrate cloud-based solutions, advanced analytics and AI into floating power generation.

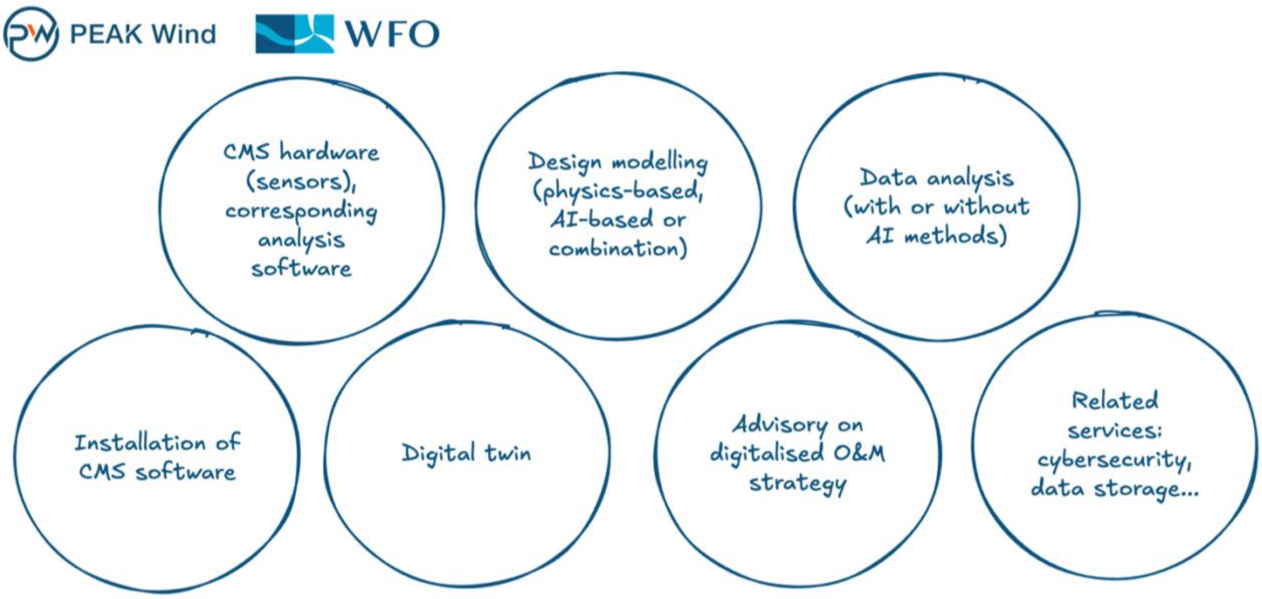

Figure 14. Broad digital solution provider capabilities. Providers offer a single or more often a combination of the above capabilities. Source: PEAK Wind & WFO

4.3 Transparency limitations which slows adoption of technology

As mentioned earlier, the turbine CMS is often provided as an additional service by the OEM, but OEMs generally have little interest in offering full transparency regarding asset performance and integrity due to the risk of claim and liability. This often results in either a refusal to provide the add-on or do it at a highly inflated price. As a protection against this, a well-prepared developer/operator adapts the WTG Service and Maintenance Agreement to capture the risk of new technologies and uncertainties in the design phase. With floating wind involving new, high-risk components beyond the WTG, a comprehensive monitoring approach is required to ensure a certain level of independence for information access. Such transparency can be achieved through early strategic planning, well-defined KPIs or by engaging a neutral third party with no interest in asset performance. This would benefit all three users of the monitoring framework: developer, operator, owner.

With a chance for performance information to be accessible by multiple stakeholders, negotiation power can tilt in favor of the CMS/digital twin users. For example, by knowing how the asset actually works, the operator can now negotiate for specific conditions in the Service and Maintenance Agreement and other supplier contracts to reduce the cost of safety factors for the unknown. The insights from the CMS/digital twin have the potential to standardise design and procurement decisions for projects using similar technology.

The digitalised O&M strategy will disrupt the status quo of information access between OEMs and developers, operators and owners, hence the importance of a transparent yet IP-compliant, secure framework to unlock the positive impacts for asset management.

4.4 Unclear cost-benefit versus business-as-usual

It is expected that digitalisation will help reduce wind energy LCOE but there is not enough information to quantify the return on investment in a generalised way but rather only on a project by project basis. Incorporating a CMS, inspection tools and/or a digital twin into a floating wind project implies higher upfront costs.[39] The point is for those costs to be recouped with a lower OPEX thanks to more strategic inspection & maintenance planning. With a clearer view on the asset's status, the project has a longer reaction time to plan inspection and preventive maintenance including vessel orders. This is important given how weather windows for floating wind maintenance (tow-to-port or onsite) are very limited. Some studies have shown how a digitalised O&M strategy leads to OPEX gains, although these are based on ideal scenarios or require more data.[40] CAPEX and OPEX figures are hard to provide without specific project details, but they would include:

- **CAPEX:** Design (strategy, interface and EPC management, design of the CMS/digital twin layout and infrastructure), Hardware procurement (cost of sensors and equipment), License fees (for CMS, software, IP), Installation (personnel), Commissioning (site acceptance test, start-up fees form software)
- **OPEX:** Replacements/Warranty (per component), Digital twin related fees (license fees for software models, dashboards, ad-hoc data processing analysis)[41]

In the end, project-specific assessments must be conducted to get a clear answer on the economic benefits of a digitalised O&M strategy. Nevertheless, the anticipated upside of a digitalised risk-based approach for commercial-scale projects is much higher than the purely prescriptive and reactive alternative.

4.5 Recommendation rather than prescription by classification societies for segments of the digitalised O&M strategy

Third-party verification can help minimise the risks associated with the uncertainties outlined in Figure 11 and Table 1. Classification and certification bodies check the reliability of the modelling framework, the verification and validation activities and sensor infrastructure (among other points). For instance, DNV's *Recommended Practice A204 Assurance of digital twins* aims to establish requirements and provide a process for developing and assuring digital twins to obtain trustworthy outputs from them. One of the purposes of ABS' Guidance Note on *Verification and Validation of Models, Simulations, and Digital Twins* is to support decision makers in assessing the credibility and acceptability of digital twins for an intended use or application. Both guidance notes recommend quality indicators that check the trustworthiness of the digital twin results, be it built-in self-diagnosis (for computation model and data quality, normal sensor operation…) or parallel visual inspection. Lloyd's Register's *Procedure for the Approval of Digital Health Management Systems* describes how it assesses

[39] A consequence for the future generation of wind farms using a standard digitalised O&M strategy may be a reduction in CAPEX because lower safety factors and redundancies can be applied to components that are being monitored. Before this can happen, the strategy must first be proven in-field

[40] O&M Subcommittee April 2023 (COREWIND Floating Wind Research Project WP4 led by Ramboll), O&M Subcommittee April 2024 (PEAK Wind internal study)

[41] PEAK Wind

the accuracy and reliability of digital twins across four levels from design to validation at commissioning and throughout the asset lifetime. In addition to the technology evaluation, the third parties check the organisation's competence in developing, operating and maintaining the digital twin. In summary, a digital twin is deemed trustworthy if it is handled by a *competent* user and has quality indicators to diagnose *itself*.[42]

More work is needed to move beyond the level of recommendations that many of these documents provide. *Rules* that link CMS/digital twin *requirements* to the impacts on a wind farm's availability, reliability or potential for lifetime extension would provide a benchmark for projects to work from. It would also help insurers and financiers in their evaluation of projects using new technologies. Indeed, track record is needed to improve the confidence in digital tools, yet the tools need to be deployed to gain that track record. Initial clear, minimum requirements could facilitate their underwriting and overcome this chicken and egg problem. As the sector evolves, so can those requirements.

[42]Certification/classification societies are even exploring the use of digital twins for their own design verification work as evidenced by their partnerships with specialist software companies, proof of digitalisation's impact beyond O&M

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6 Appendix – Definitions

Artificial intelligence refers to the simulation of human-like intelligence by machines, enabling them to perform tasks such as reasoning, problem-solving, perception, and language understanding. Some AI systems use machine learning but not all do.

Big data refers to datasets so large, fast, or complex that traditional tools cannot efficiently handle them. It is defined by the **"5 Vs": Volume, Velocity, Variety, Veracity, and Value**. Big data technologies enable the storage, processing, analysis and transmission of diverse data types at scale to uncover insights and support decision-making. Managing big data will help make decisions based on data at the wind farm level (dozens of turbines) or throughout the whole life cycle (design to decommissioning). With this big picture view there is also a chance to identify hidden relationships. One key consideration will have to be the period of time that data should be saved as there is a limited capacity based on hardware technology. Note that what is meant by big data and the ways a user can work with it is continuously evolving as storage gets cheaper, computing power increases or new software is developed.

Condition monitoring system (CMS) is a periodic or real-time monitoring framework made up of sensors, data acquisition feeds and analytics to assess the performance and structural integrity of the FOWT’s key components. The CMS complements inspection campaigns to reduce cost and risk. The information from the CMS supports preventive maintenance which can enhance operational efficiency (reduce downtime and cost) as well as extend the FOWT’s life.

Data analytics focuses more specifically on analysing data to draw conclusions and support decision-making, often through visualisation and business intelligence tools. It includes inspecting, cleaning, transforming and modelling data. Anomaly detection in a FOWT digital twin is a form of data analytics.

Data management is the policy framework for collecting, storing, preserving and accessing data. It enables the easy identification of data in storage (tagged with metadata using controlled ontology) and its sharing (thanks to common metadata schema across organisations, data portals). Source: Clifton et al. 2023 *Grand challenges in the digitalisation of wind energy.*

Data science involves extracting insights from data using techniques from statistics, machine learning and computer science.

Digitalisation is the organisational and sector-wide use of data and digital technologies to improve efficiency, create insights and develop products and services. **Digital technologies** include data management, data science, data analytics, storage, connectivity, computational power etc. to exploit the ever-increasing amount of data. Artificial intelligence can be used across these tools and approaches. Source: Clifton et al. 2023 *Grand challenges in the digitalisation of wind energy.*

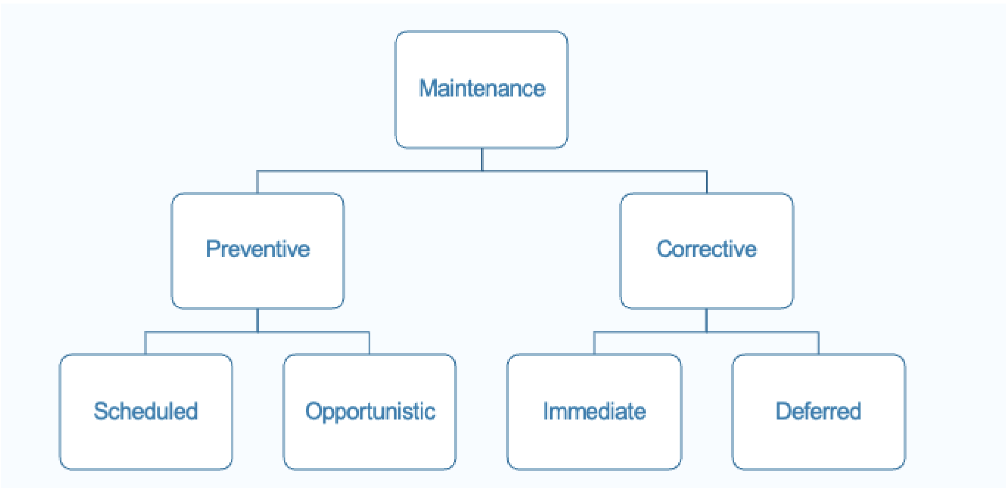
Digital twin – see definition in box of page 11.

Integrity management is a process that can ensure the FOWT/wind farm's fitness-for-service over its entire life cycle. Integrity management programmes categorise risks based on their likelihood and severity, which then guide the use of inspection and monitoring to detect abnormal conditions or factors outside the original design envelope. Should an issue arise, intervention, repair & replacement procedures should be enacted to protect the asset against accident or loss.

Internet of Things (IoT) is a web of physical objects – things – that are connected to each other and users through the internet. The data can be captured by sensors and moves from the object (hardware) to the user through discrete layers (software). This is the technology behind condition monitoring.

Machine learning (ML) is a subset of AI that enables systems to learn patterns and make decisions or predictions from data without being explicitly programmed for every scenario. It includes supervised, unsupervised, and reinforcement learning approaches. The more data fed into a machine learning algorithm, the more accurate the pattern prediction becomes.

There are two main categories of **maintenance**: preventive (before failure) and corrective (after failure). Within preventive maintenance, there are scheduled and opportunistic repairs. Opportunistic repairs are done in conjunction with routine maintenance events. Scheduled repairs are additional events based on the condition monitoring information (e.g. upon sensor warning). Corrective maintenance is either immediate or deferred.



Source: PEAK Wind