Energy Reports 9 (2023) 103–108

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Towards fully autonomous floating offshore wind farm operation & maintenance[☆]

Evi Elisa Ambarita [*], Anniken Karlsen, Ottar Osen, Agus Hasan

Department of ICT and Natural Sciences, Norwegian University of Science and Technology, Ålesund, Norway

A R T I C L E I N F O

Keywords:
Floating offshore wind farm
Autonomous system
Digital twin
Industry 4.0
Operation and maintenance

A B S T R A C T

Wind energy is one of the most versatile and promising sustainable energy solutions. Wind energy can be harvested in both onshore and offshore environments. Due to the environmental and societal impacts of onshore wind farms, the focus on developing offshore wind farms has been steadily increasing. For deep-water areas, floating wind turbine solutions have been developed in the past two decades. Each wind turbine is mounted on a floating structure and connected to a mooring system. While the floating wind turbine technology enables electricity generation in water depths where fixed-foundation turbines are not feasible, operation and maintenance (O&M) have become serious issues. This paper investigates the challenges and potential enabling technologies for the development of autonomous floating offshore wind farms. In particular, the paper explores the potential utilization of information and communication technology (ICT) and robotics toward fully autonomous floating offshore wind farm O&M, aiming for cost reduction and improved operational safety. The presented solutions cover fundamental aspects in floating platform design, remote operation in the form of digital twins, autonomous underwater robots and surface vehicles, and eco-friendly energy storage.

1. Introduction

To achieve the net zero target of CO_2 emission by 2050, as declared in the Paris Agreement, wind energy has become one of the most promising sustainable energy solutions. China installed a total of 52 gigawatts (GW) of wind power capacity in 2021, while the United States has set a national deployment target of 30 GW of offshore wind power by 2030 (Lee and Zhao, 2022). Furthermore, Germany, Denmark, Belgium, and the Netherlands have set a joint goal of generating at least 150 GW of offshore wind power by 2050 to end the use of fossil fuels (Buljan and Four, 2022). In Norway, the government has set a new offshore wind target of 30 GW by 2040 (Hovland, 2022), which is quite realistic considering the huge potential of offshore wind energy in terms of the mean wind speed. Fig. 1 shows the maps of the mean wind speed (left) and water depth (right) in Scandinavia. In the western coast of Norway, the water depth is more than 200 m while the mean wind speed is above 10 m/s. All these ambitions show that the technological developments in the wind power sector are on the rise, something which will directly affect the requirements for operation and maintenance (O&M) in offshore wind farms.

The amount of generated power in a wind farm can be increased either by multiplying the number of installed turbines or by enlarging the size of the turbines. For onshore wind turbines, the limited area often becomes a challenge as regards increasing the number of installed turbines. Meanwhile for offshore wind turbines, as the turbine size increases, the location of the turbine installation is further away from the shore due to social and environmental impacts. In most areas, distance from the shore is directly proportional to the water depth. An increased water depth results in higher foundation costs for a bottom-fixed offshore wind turbine. Floating wind turbine structures can be seen as a solution for deep water areas. For example, the Hywind Tampen, which is the largest floating wind farm in the World, is located 140 kilometers off the coast of Norway. The water depth in the Tampen area is between 260 and 300 m (Qaiser et al., 2022). Each wind turbine is mounted on a floating structure and connected to a mooring system. While the floating wind turbine technology enables electricity generation in water depths where fixed-foundation turbines are not feasible, operation and maintenance (O&M) have become serious issues.

As regards floating offshore wind farms, the needs for installation and O&M are relatively costly compared to onshore wind farms. It

---

[☆] 2023 8th International Conference on Sustainable and Renewable Energy Engineering (ICSREE 2023) 11–13 May, Nice, France.

[*] Corresponding author.
E-mail address: evi.e.ambarita@ntnu.no (E.E. Ambarita).

https://doi.org/10.1016/j.egyr.2023.09.148
Received 31 August 2023; Accepted 24 September 2023

involves service vehicles for installation, divers/remotely operated vehicles (ROVs) for inspection, and additional equipment for power distribution. In order to facilitate the O&M processes and to reduce the costs, advanced technologies pertaining to the development of the offshore wind industry towards autonomy are necessary. In this paper, we present challenges and potential enabling technologies for the development of autonomous floating offshore wind farms. In particular, the paper explores the potential utilization of information and communication technology (ICT) and robotics towards autonomous floating offshore wind farm O&M, aiming for cost reduction and improved operational safety.

2. Challenges in O&M of floating wind farms

The O&M of floating wind farms is a significant cost driver, accounting for a substantial portion of the total lifecycle costs for these offshore wind energy facilities (Stehly and Beiter, 2018). Several factors contribute to the high costs and difficulties associated with the O&M of floating wind farms. For example, the unpredictable weather conditions and harsh environmental conditions of the offshore environment can pose significant challenges for maintenance and repairs. The installation position of these wind farms, far from shore, adds to the difficulties and costs associated with accessing the turbines for maintenance and repairs. Additionally, the maintenance needs of the turbines, mooring systems, and other components of floating wind farms can be substantial, requiring specialized equipment and expertise to carry out effectively. Ensuring operational safety is also critical, given the hazardous conditions in which these wind farms are located. This section explores the challenges associated with O&M of floating wind farms as a basis for further development aimed at reducing O&M costs.

2.1. Harsh environment

The wind speed in offshore is higher than onshore, as there are no physical barriers to block the wind, resulting in the development of larger wind turbines with higher levels of generated power. However, harsh weather conditions at sea, such as very high-speed winds from hurricanes and unstable sea waves, present challenges leading to increased turbine wear-down and damage. Harsh offshore environments can also endanger operational safety for on-site maintenance when unscheduled visits are needed due to unexpected turbine shutdowns. Long distances from the shore also generate longer waiting times for repairs and longer out-of-service times. Bad weather makes it difficult for vessels to access the site due to sea-state limitations on maritime operations. As a consequence of this, it is imperative to remotely control and monitor all sensors on the turbine in order to analyze real-time data to prevent and predict failures.

The fluctuating wind speeds in offshore can lead to inconsistent power generation from wind turbines, resulting in intermittent power supply to the grid. This variability in power output can create challenges for grid stability and reliability. Additionally, power vibration caused by wind speed fluctuations can induce mechanical stress and strain on the components of wind turbines and their associated infrastructure. This can potentially lead to increased wear and tear, fatigue, and even structural damage over time. Such mechanical stresses may impact the lifespan and performance of wind turbines, necessitating maintenance and repair activities that can incur additional costs.

2.2. Accessibility

Offshore wind farms present significant accessibility challenges due to their remote and difficult-to-reach locations, often situated in harsh sea environments. This makes it difficult for maintenance and service personnel to reach the turbines for regular checks, inspections, and repairs. The rough sea conditions, such as high winds and waves, can also make it extremely challenging and dangerous for technicians to access the turbines, posing a threat to their safety. In addition to the difficulties in accessing the turbines, the logistics of transporting the necessary equipment, supplies, and personnel to the wind farm site can also be a major challenge. Overall, the remote location, harsh sea conditions, and

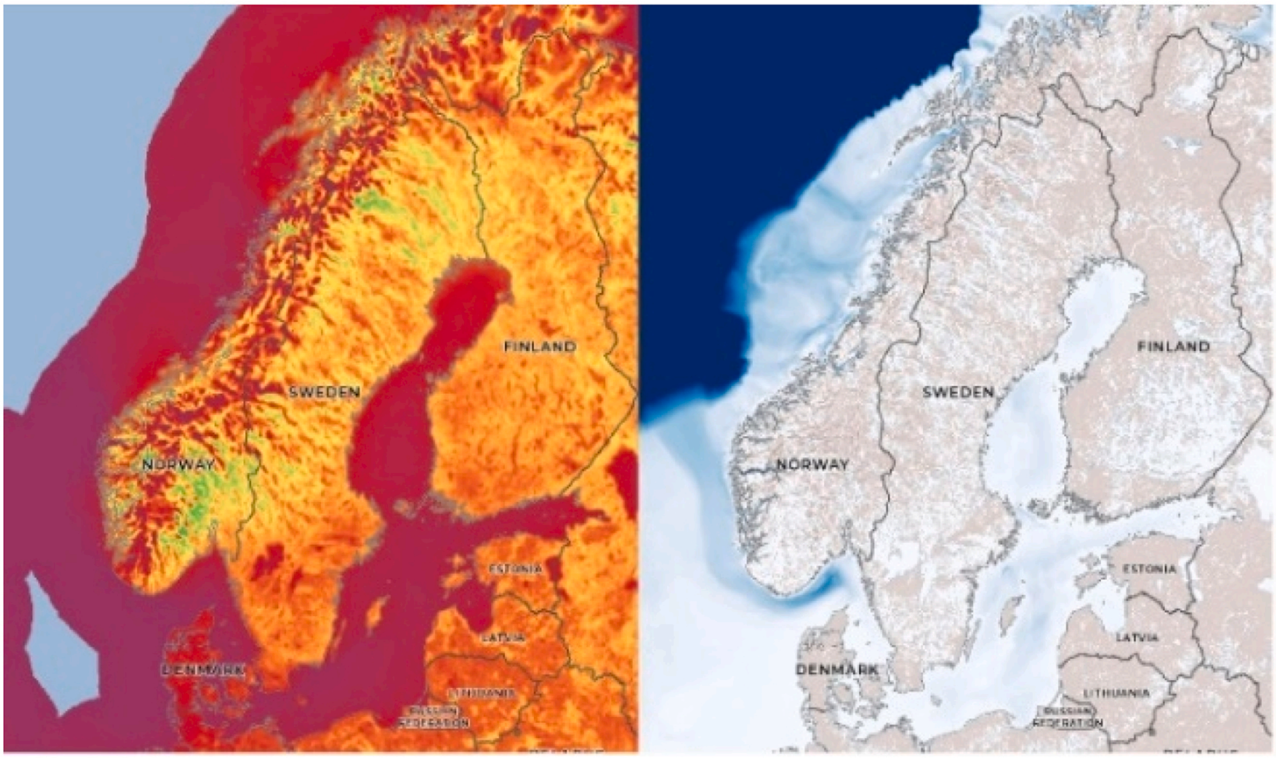

Fig. 1. Maps of mean wind speed and water depth in Scandinavia.

logistics challenges associated with offshore wind farms highlight the importance of developing effective and efficient strategies for accessing the turbines, as well as innovative technologies that can help overcome these challenges.

2.3. High O&M costs

Due to the size and noise pollution, larger floating wind turbines are mostly installed far from the shore which results in limitations and difficulties in accessing the site. When turbines need maintenance or repair, technicians and equipment must travel a long distance to reach the turbines, increasing turbine downtime. Moreover, it requires a service vehicle, which is not always available, with specific capabilities such as gangways, a craft, helideck, and cranes, to transport maintenance crew and equipment. Operation and maintenance of offshore wind farms entail substantial costs. In Industry 4.0, referring to intelligent networking, existing technologies in use in the floating wind farm industry can be advanced with the help of ICT to significantly reduce O&M costs. The improvement of sensor systems, robotics, remote control, and modeling methods is expected to be able to contribute to autonomous O&M systems for floating wind farms, with the aim of reducing the need for human intervention and simplifying the O&M process.

2.4. Deeper water

Floating wind turbines use mooring systems to keep the turbine floating. Generally, each floating turbine has multiple mooring lines that are anchored to the seabed and fastened to the support structure. These underwater mooring lines need scheduled inspections and maintenance to check for cracks and fatigue. Deep-water conditions render it impossible to observe only from above the water, resulting in divers or ROVs being required for reaching the seabed. An autonomous system for underwater inspection and maintenance is also urgently needed for the O&M of floating wind farms.

2.5. Installation

Floating offshore wind farms present several challenges during the installation process. Installing floating wind turbines requires advanced engineering and technical skills, as well as specialized equipment, making the installation process more complex compared to traditional fixed-bottom offshore wind farms. Furthermore, adverse weather conditions, such as high winds and waves, can make it difficult or even impossible to install floating wind turbines, and can also pose a threat to the safety of workers. Moreover, floating wind farms must be located in deep waters, which can be challenging to access and install equipment in, especially in areas with difficult sea conditions. These challenges highlight the need for the development of innovative technologies and installation methods that can help overcome these barriers and make the installation process for floating offshore wind farms more efficient and cost-effective.

Given these challenges, it is important to focus on developing new strategies and technologies to reduce the O&M costs of floating wind farms. This includes exploring new ways to improve the reliability and durability of the turbines and other components, as well as developing more efficient and cost-effective maintenance and repair strategies. By addressing these challenges and reducing the costs associated with O&M, the potential for widespread deployment of floating wind farms can be realized, providing a significant contribution to the growth of renewable energy.

3. Enabling technologies for O&M of floating wind farms

This section presents enabling technologies that have a high potential to be adopted from other industries – such as manufacturing, oil, and gas – and be implemented into the offshore wind sector. We present Fig. 2 as an illustration of how these enabling technologies contribute to operating and maintaining floating wind farms toward autonomous systems. It shows the future O&M of offshore wind turbines. The use of autonomous aerial vehicles and subsea robotics for inspection and maintenance will be vital.

3.1. Floating turbine design

As the development of offshore wind turbines has massively grown, the design of floating wind turbines is also evolving, especially regarding turbine foundations. Spar type, as seen in Fig. 2 on the left, is a well-proven concept for offshore turbine foundations, i.e., a ballast-stabilized simple structure with good hydrodynamic performance and high stability (Kaptan et al., 2022). It is a tube with denser ballast fluid located at the end of the platform to bring down the center of gravity under the center of buoyancy. The first large-scale demo of a spar-type floating turbine was carried out by Equinor ASA – a Norwegian state-owned multinational energy company – concerning the passive ballast and simple geometry design (Muliawan et al., 2013). In (Hegseth et al., 2020), the authors performed the optimized design of a 10 MW floating wind turbine with a spar buoy foundation at a water depth of 320 m.

On the other hand, a barge type, as seen in Fig. 2 on the right, is a floating concept expanded from a semi-submersible model. It utilizes the distributed buoyancy-stabilized type for stability by using the water-plane area and the catenary moorings connected to the seabed. The barge platform is designed in such a way as to absorb wave loads and decrease the floater motion. The advantage of the barge type is its structural simplicity, resulting in reducing the total weight, construction, and maintenance costs. In (Yang et al., 2022), the authors investigated a 1:20 scaled model of a barge-type floating offshore wind turbine which consists of a 5 MW wind turbine with a 90 m hub height and a water depth of 70 m in the western Taiwan offshore water area.

Moreover, by adopting both barge and semi-submersible types, the Saitec company created a new floating platform technology called SATH consisting of single-point mooring and reinforced concrete on horizontal twin hulls. By utilizing a 2 MW wind turbine as their demonstrator it was proven that the stability system was well-designed for hydrodynamic performance. This technology is suitable for shallow and deep waters due to its low draft, resulting in the potential for easy installation at most ports.

3.2. Remote operation

By referring to the challenges mentioned above, the urgency of

Fig. 2. Illustration of the autonomous floating wind farms of the future (The photos of autonomous surface).

remote operation for floating wind farm O&M is high, concerning both O&M cost reduction and operational safety during maintenance. Furthermore, by receiving real-time data from sensors, data can be analyzed to create a digital model able to exchange information with the physical device for improved decision-making. In this case, it can constitute a scheduled preventive maintenance and fatigue diagnosis. This section explores several enabling technologies that can be applied in offshore wind farms in order to control and operate the turbines remotely.

3.2.1. *Digital twin*

A digital twin is a digital replica of a physical asset or system which functions to mirror the life of its corresponding twin. Digital twins reflect real-time data of the physical asset to forecast the future behavior of the asset or system (Tygesen et al., 2018). The bidirectional communication between digital assets and physical assets provides digital twins as a reliable solution for the management of wind power plants (Cisterna et al., 2022). It is used to track the lifecycle of the device from modeling to disposal in order to estimate the remaining useful life of the turbine.

Digital twin technology has been implemented in other industries, particularly in the manufacturing industry. In floating offshore wind farms, digital twins are used to remotely control and monitor turbines for predictive maintenance and to optimize inspection intervals (Fox et al., 2022). Fig. 3 shows how the digital turbine (the right one) is designed as similarly as possible to the actual turbines (the left one). It represents the physical assets of offshore wind farms for condition monitoring, real-time prediction, and improved decision-making.

In Industry 4.0, there is a standardization for digital representation of industrial assets to build the interoperable digital twin called Asset Administration Shell (AAS) (Benesl et al., 2022). AAS is a machine readable, technology device-agnostic description of a component that supplies access to all its functions and properties. By implementing AAS in digital twin for offshore wind farms, the information exchange not only occurs among the assets, but also across companies and supply chains, from technical function to business model, which, in turn, leads to increased productivity and effectiveness. Referring to the Reference Architecture Model for Industry 4.0 (RAMI 4.0), a three-dimensional model consists of hierarchy levels, life cycle & value stream, and layers. The AAS framework based on RAMI4.0 enables the comprehensive management of the entire life cycle of wind turbines across the complete value chain, from initial needs assessments to the utilization of data received from end users for the development of upcoming designs.

3.2.2. *Sensor systems*

The implementation of digital twins is reliant on sensor systems, which have experienced a marked increase in the volume of data generated in recent years. The operation and performance of wind turbines are monitored by a variety of sensors serving a specific purpose. Eddy current sensors are employed to observe the lubricating gap of the shaft, as temperature fluctuations can alter the viscosity of lubricants and affect the shaft's rotation properties. Displacement sensors are utilized to monitor the structural stability of the tower and nacelle. The measurement of wind speed is facilitated through the utilization of LiDAR-based wind speed sensors to forecast the generated power. Accelerometers are employed to monitor tower sway, nacelle rotation, and gearbox vibrations. The historical and real-time data from vibration signals and temperature sensors are considered the most detectable indicators for predicting the potential gearbox failure which represents the highest failure rates of wind turbine components.

The real-time data collected by sensors play a significant role in realizing digital twins for offshore wind farms, as it enables functions such as condition monitoring, generated power forecasting, and predictive maintenance. To optimize productivity, it is essential to have intelligent sensors in place that are capable of processing data on-site, rather than transmitting raw data to the central control system for analysis. The data received from sensors are required to be automatically integrated into a digital twin framework in the communication system for the provision of decision-making support.

3.2.3. *Communication*

Industry 4.0 was enabled by interconnecting systems, often through the internet, or by using technology and protocols from the internet in an industrial setting. Much of the technology utilized in the fourth industrial revolution, such as robots, has been available for a long time. However, the possibility to "connect everything with everything everywhere" has enabled the industry to take industrial automation to a new level. These communication technologies are often called IoT (Internet of Things), for industrial use known as IIoT (Industrial IoT) (Lu et al., 2021).

The communication system within the framework of Industry 4.0 plays a crucial role in fostering interconnectivity among all assets, thus enabling automatic integration without human intervention. Moreover, the communication system in the digital twin platform must perform interoperability among all involved stakeholders, where specific data can be exchanged across sectors. There are three types of communication modes in the context of AAS (Ye et al., 2021); namely (i) passive

Fig. 3. Visualization of digital twin for offshore wind farms.

type with file exchange mode using uniform file formats such as XML and JSON, (ii) reactive type with server-client communication mode using API such as MQTT and OPC-UA, (iii) proactive type with peer-to-peer interaction through a standardized interface with a shared syntax and semantics base. The proactive type of AAS is essential for autonomous communication among the integrated components and stakeholders, in accordance with the industry 4.0 standardization.

3.3. *Offshore robotics*

The idea of offshore robotics is significantly beneficial for O&M of floating wind farms, not only as it pertains to O&M cost reduction, but also to increased productivity. The subsea ROV has been a workhorse in maritime operations for decades. These ROVs have typically replaced divers and perform subsea tasks both cheaper, deeper, and more effectively with no risk to human lives. They require highly trained operators (ROV pilots) located in support vessels. NTNU – The Norwegian University of Science and Technology – is taking part in the development of the next generation of enabling technologies for maritime operations, including O&M of floating wind farms, through the NTNU AMOS (Autonomous Marine Operations and Systems). This project focuses on autonomous unmanned vehicle systems, including underwater vehicles, aerial vehicles, and surface vessels to support marine operations.

3.3.1. *Autonomous underwater robots*

Autonomous underwater robots, as seen in Fig. 4, are being developed for subsea inspection, maintenance, and repair (IMR). The Eelume robot consists of robotic arms with a flexible body that is designed to stay permanently on the seabed and to be completely autonomous or remotely controlled by operators. It is equipped with sensors performing environmental surveys on subsea structures (Liljeback and Mills, 2017). Its entire body has batteries, lights, sensors, and tool modules used according to its role underwater. Eelume's goal is to provide a reliable method for subsea maintenance. This could provide offshore wind farm operators with the ability to replace divers and ROVs in conducting subsea IMR to minimize risk, time, and expenses. Moreover, there is also an underwater drone known as Blueye with functions such as lights, sonars, cameras, positioning systems, and sensors for underwater inspection (Bellingmo, 2020).

3.3.2. *Autonomous surface vessels*

An autonomous surface vessel is a vessel that has achieved a level of autonomy in its employment, resulting in a cost-effective and safe method of marine monitoring. It is generally used to record oceanographic data, navigate reefs, and collect water samples. For offshore wind farms, it aids in inspecting the support structure and in monitoring the mooring line from the water surface for improved decision-making in the maintenance schedule.

Fig. 4. The Eelume underwater robot was developed by NTNU and Equinor.

3.3.3. *Offshore service vessels*

As the number of offshore wind turbines increases, the need for offshore service vessels increases accordingly for O&M, especially when the installation is located further from shore, and in harsh environments. Together with offshore service vessels, the walk-to-work (W2W) approach facilitates the process of transferring technicians from service vessels to wind turbines for on-site maintenance, as seen in Fig. 2. In (Guanche et al., 2016), the authors compared two vessels for the W2W of floating wind turbines, namely a catamaran with a fender and a supply vessel with a motion-compensated gangway. The catamaran has potential access only if there is no slip between the ladder landing platform and the vessel fender. Meanwhile, the supply vessel is appropriate when the gangway movement is below the compensated limit of the hydraulic system. The authors concluded that the accessibility potential per year by a vessel with gangways is nearly four times greater than by a catamaran with a fender.

W2W requires service vessels to provide a dynamic positioning (DP) system with an offshore gangway considering motion compensation in terms of floating platforms. In (Huang et al., 2018), the authors reported the analyses of W2W implementation for the oil and gas industry, as it pertained to the gangway's complex dynamic motion on vertical and horizontal planes due to the multi-body hydrodynamic interaction. They presented numerical and experimental analyses of dynamic gangway response between floating production storage and offloading (FPSO) vessels and monohull flotels. A similar concept can be applied in maintaining offshore wind farms for increased efficiency and technician safety.

3.4. *Offshore energy storage*

Challenging offshore weather conditions cause large fluctuations in power generation resulting in the destabilization of the power grid. Implementing energy storage systems, such as batteries, can help mitigate the intermittent nature of wind power generation. Energy storage systems enable optimal reconciliation of supply and demand, thereby reducing the variability in power output and stabilizing the grid. In (Yessica et al., 2022), the authors reviewed different alternatives for energy storage solutions for the offshore application, such as batteries, supercapacitors, flywheels energy storage, hydro-pneumatic energy storage, hydrogen storage, ammonia-based energy storage, and compressed air energy storage. They concluded that Li-ion batteries and compressed air energy storage constitute the most promising energy storage technology, which can meet the needs of offshore energy solutions based on its level of readiness and cohesiveness.

By adopting the concept of compressed air energy storage, utilizing water instead, the Ocean Grazer B.V company introduced an advanced solution for offshore energy storage by applying a pumped hydro system called an ocean battery. Its mechanism system adopts the hydro dam technology utilizing the pressure difference between atmospheric pressure and hydrostatic pressure (Hut, 2020). It consists of two reservoirs: the flexible bladders on the seabed as the pressurizing reservoir and the rigid one as the depressurizing reservoir. For the charging period, water from the rigid reservoir is pumped into the flexible reservoir where the energy is stored as potential energy under high pressure (Stegenga, 2021). When the energy is needed, water from the flexible reservoir flows back into the rigid reservoir converted back into electricity. The concept of ocean batteries is an eco-friendly energy storage solution for up to GWh scale since it does not contain any rare earth metal, i.e., lithium (Hut, 2020).

Moreover, another potential solution to address the challenges of power vibration caused by variable wind speeds is the implementation of grid-forming converters (Zhang et al., 2021). These sophisticated power electronic devices actively control the voltage and frequency of the generated output power, contributing to grid stability. Together with the development of advanced control strategies, such as predictive control algorithms that anticipate wind speed changes and adjust turbine operation in real-time to maintain stable power output, power fluctuations and associated vibrations can be effectively minimized.

4. Conclusion and future work

In this paper, we have presented a list of challenges for O&M of floating offshore wind farms. We argue that these challenges will drive the offshore wind industry to move towards fully autonomous O&M, which aims to reduce costs and improve safety. Furthermore, to show the full potential of autonomy in O&M, we have presented a list of enabling technologies, which have been maturely implemented in other industries, such as the offshore oil and gas industry. Efforts have been made when investigating further improvements which cover all aspects of O&M, such as novel system design, remote operation, and vessel maintenance. With the help of ICT and IoT in the context of Industry 4.0, O&M autonomy can potentially help to reach the net zero target by 2050.

As a follow-up to this paper, we will develop a digital twin platform for the offshore wind farm industry. Future works include investigation of architecture design, data management, predictive analytics, information modelling, and system integration. AAS-based digital twin framework will be developed upon the industry 4.0 standardization. The communication layer for the framework will be established using OPC-UA to perform the interoperability. The OPC UA-based AAS will be of a proactive type, such that AASs can autonomously communicate with each other to perform peer-to-peer interaction among AAS. This interoperable digital twin aims for increased productivity and improved decision-making. It is expected that future work will contribute towards autonomous floating offshore wind farm O&M.

Declaration of Competing Interest

The authors declare no conflict of interest.

Data availability

No data was used for the research described in the article.

Acknowledgements

This research is part of the EU project PERSEUS (Doctoral Program for Integrated Research Activities to Unlock a Potential of Top-level Researchers in Digital Transformation for Sustainability), Project Agreement No 101034240.

References

Bellingmo P.R. DP control system for blueye pioneer. Master thesis in Marine Tech. NTNU, Trondheim, 2020.

Benesl, T., Kaczmarczyk, V., Sykora, T., Arm, J., Dvorsky, P., Husak, M., et al., 2022. Asset administration shell - manufacturing processes energy optimization. IFAC PapersOnLine 55 (4), 334–339.

Buljan A. Four E.U. countries set joint offshore wind target of 150 GW by 2050. ⟨https://www.offshore-energy.biz/four-eu-countries-set-joint-offshore-wind-target-of-150-gw-by-2050/⟩ accessed on August 04, 2022.

Cisterna, A.R., Salimbeni, S., Andaloro, G., 2022. Digital twin for the management of wind power plants. Published by ECRES, Istanbul.

Fox, H., Pillai, A.C., Friedrich, D., Collu, M., Dawood, T., Johanning, L., 2022. A review of predictive and prescriptive offshore wind farm operation and maintenance. Energies 15, 504.

Guanche, R., Martini, M., Jurado, A., Losada, I.J., 2016. Walk-to-work accessibility assessment for floating offshore wind turbines. Ocean Engineering 116, 216–225.

Hegseth, J.M., Bachynski, E.E., Martins, J.R.R.A., 2020. Integrated design optimization of spar floating wind turbines. Marine Structures 72, 102771.

Hovland K.M. The government sets new targets for offshore wind. ⟨https://e24.no/olje-og-energi/i/34G8ad/regjeringen-setter-nye-maal-for-havvind⟩ accessed on August 04, 2022.

Huang, W., Li, B., Chen, X., Araujo, R., 2018. Numerical and experimental studies on dynamic gangway response between monohull flotel and FPSO in non-parallel side-by-side configuration. Ocean Engineering 149, 341–357.

Hut, L.Y., 2020. Investigating the structural behaviour of the Ocean Battery. Research Project in Industrial Eng. and Management. Univ of Groningen & Ocean Grazer (Sept.).

Kaptan, M., Skaare, B., Jiang, Z., Ong, M.C., 2022. Analysis of spar and semi-submersible floating wind concepts with respect to human exposure to motion during maintenance operations. Marine Structures 82, 103145.

Lee, J., Zhao, F., 2022. GWEC | Global wind report. Global Wind Energy Council.

Liljeback P., Mills R. Eelume: A Flexible and Subsea Resident IMR Vehicle. OCEAN 2017 - Aberdeen, 2017:1–4. ⟨doi:10.1109/OCEANSE.2017.8084826⟩.

Lu, Q., Xiang, Li, Guanyi, Li, Mei, Li, Zhou, J., Liu, J., et al., 2021. A general asset administration shell platform for production line design. IEEE 1st Int Conf on Digital Twins and Parallel Intelligence (DTPI).

Muliawan, M.J., Karimirad, M., Moan, T., 2013. Dynamic response and power performance of a combined spar-type floating wind turbine and coaxial floating wave energy converter. Renewable energy 50, 47–57.

Qaiser M.T., Ejaz J., Osen O., Hasan, A. Digital Twin-Driven Energy Modelling of Hywind Tampen Floating Wind Farm, International Conference on Renewable Energy and Conservation, November 2022, Paris, France.

Stegenga, W.J., 2021. Development and validation of an analytical flow model for the buried Ocean Battery. Master Thesis in mech eng Univ of Groningen & Ocean Grazer (Aug).

Stehly, T., Beiter, P., 2018. Cost of Wind Energy Review. Technical Report. National Renewable Energy Laboratory 2019.

The photos of autonomous surface vessel were taken from ⟨www.ares.global⟩, and the photo of offshore service vessel was taken from ⟨www.alimak.com⟩.

Tygesen U.T., Jespsen M.S., Vestermark J., Dollerup N., Pedersen A. The true digital twin concept for fatigue reassessment of marine structures. ASME 2018 37th Int. Conf on Ocean, Offshore and Arctiv Eng (OMAE 2018). Madrid, Spain, June, 2018.

Yang, R.-Y., Wang, C.-W., Huang, C.-C., Chung, C.-H., Chen, C.-P., Huang, C.-J., 2022. The 1:20 scaled hydraulic model test and field experiment of barge-type floating offshore wind turbine system. Ocean Engineering 247, 110486.

Ye, X., Hong, S.H., Song, W.S., Kim, Y.C., Zhang, X., 2021. An industry 4.0 Asset Administration Shell-Enabled digital solution for robot-based manufacturing systems. IEEE Access 9, 154448–154459.

Yessica, A.-P., Elvia, C.-P., Pierluigi, S.R., Francesco, F., 2022. Energy storage solutions for offshore applications. Energies 15 (17), 6153.

Zhang, H., Xiang, W., Lin, W., Wen, J., 2021. Grid forming converters in renewable energy sources dominated power grid: control strategy, stability, application, and challenges. Journal of Modern Power Systems and Clean Energy 9 (6), 1239–1256.