Wind energy digitalisation towards 2030

Cost reduction, better performance, safer operations

WindEurope

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This report analyses the status of digitalisation of the wind energy sector today and presents WindEurope's vision on the evolution of digital applications and technologies towards 2030. The analysis is based on WindEurope's internal analysis and consultations with the members of its Task Force O&M Digital.

TEXT AND ANALYSIS:
WindEurope Business Intelligence
Vasiliki Klonari
Georgios Papachristos
Daniel Fraile

EDITOR:
Rory O'Sullivan

DESIGN:
Lin Van de Velde, Drukvorm

PHOTO COVER:
PPstock for Shutterstock

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MORE INFORMATION:
policy@windeurope.org
+32 2 213 18 68

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EXECUTIVE SUMMARY

Over the last two decades digitalisation has been transforming the power sector in a remarkable way. It has helped to reduce the costs of various grid and generation applications, to improve their performance and to multiply environmental benefits for energy consumers. This transformation has also been affecting the entire wind energy supply chain, from wind turbine manufacturing to daily wind farm operation and decommissioning. In the next decade the further digitalisation of wind farm construction, operation and maintenance (O&M) will be a major driver for improving performance and reducing costs and financial risk.

The potential benefits are clear. But quantifying the exact benefits for each of the parties and implementing innovative solutions is not straightforward. As it stands, universal definitions to describe major digital applications and metrics to assess their benefits are lacking. Given the increasing complexity of wind farm operations, it is very difficult to compare benefits from different digital applications.

This report defines major digital applications in wind O&M and a set of digital applications in wind turbine manufacturing and construction. It also presents the use of generic technologies enabling many of the previous digital applications i.e. big data, 5G technology. For each application, the report lists the potential benefits and challenges but also the technologies that are used today and will be used more over the next decade.

Five major categories of technologies are identified: real time analysis, Internet of Things gateways, diagnostic analytics, prescriptive analytics and automation. Each one of these includes various tools such as machine learning and artificial intelligence, condition monitoring, robotics, augmented reality, digital twin, that are usually combined to enable the various applications. The report presents several case studies of deployed technologies showing how digitalisation has transformed the wind sector.

Secondly, the report investigates the major role of data in enabling the previous digital applications. Thirdly, considering the current deployment of digital applications and respective technology trends, the report presents WindEurope's vision towards a digital wind sector by 2030 and a set of recommendations to make this real:

- Develop reliable universal metrics and knowledge sharing platforms to understand the benefits of digital applications
- Develop a universal wind data standard going into the necessary level of detail, complementing currently deployed international standards
- Establish efficient data sharing practices within organisations and with third parties supported by a universal wind data standard and adequate contractual templates
- Validate the technologies and make them transferable to different contexts at low cost thanks to well-established data sharing practices
- Develop the necessary skills combining digitalisation and wind technology expertise with dedicated energy digitalisation study programmes in universities and workforce training courses

LIST OF ABBREVIATIONS

ACC	Advance casting cell
AEP	Annual energy production
AI	Artificial intelligence
AIS	Automatic identification system
API	Application programming interface
AR	Augmented reality
BoP	Balance of plant
CCTV	Closed-circuit television
CFD	Computational fluid dynamics
CIM	Common information model
CMMS	Computerised maintenance management system
CMS	Condition monitoring system
DAC	Digital automation cloud
DTS	Distributed temperature sensing
EBIT	Earnings before interest and taxes
ECMWF	European Centre for Medium-Range Weather Forecast
EPC	Engineering, procurement and construction
GFS	Global forecast system
GIS	Geographic information system
ICCP	Inter-control centre communications protocol
IEC	International Electrotechnical Commission
IIoT	Industrial Internet of Things
IoT	Internet of Things
IRR	Internal rate of return
IT	Information technology
KPI	Key performance indicator

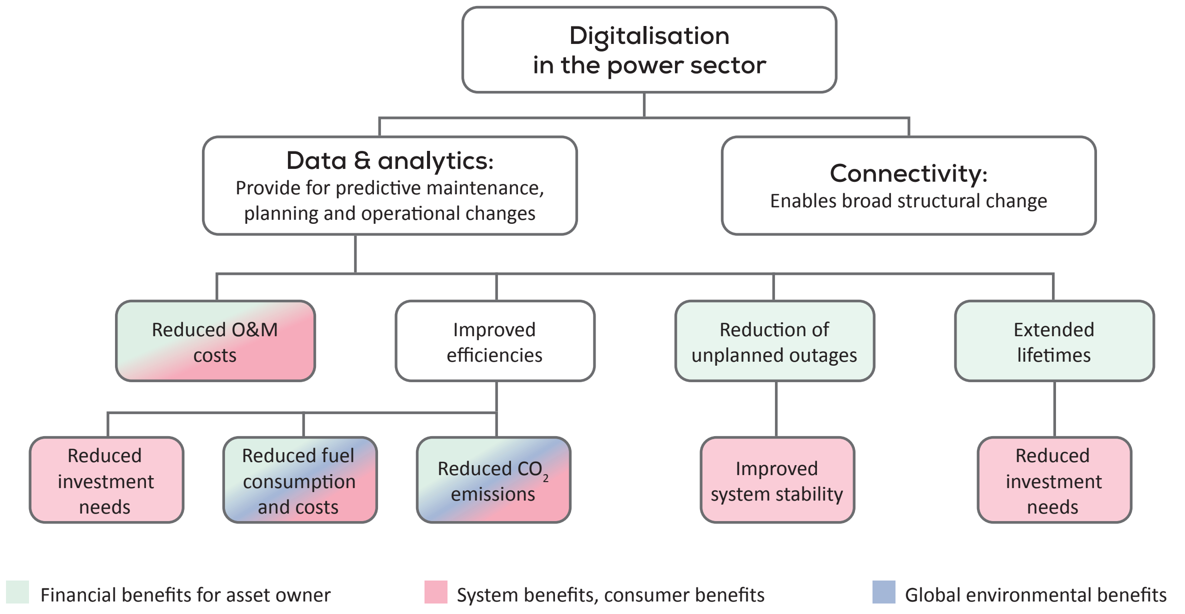
ML	Machine learning
NPV	Net present value
O&AM	Operation & asset management
O&M	Operation & maintenance
OEM	Original equipment manufacturers
OHVS	Offshore high voltage substation
OPEX	Operational expenditure
PV	Photovoltaic
QHSSE	Quality, health, safety, security, environment
RCA	Root cause analysis
RCC	Remote control centre
RPA	Robotic process automation
RUL	Remaining useful life
SCADA	Supervisory control and data acquisition
SOV	Service operation vessel
TSO	Transmission system operator
UAV	Unmanned aerial vehicle
UI	User interface
USV	Uncrewed surface vessel
VHF	Very high frequency
VR	Virtual reality
WiBB	Wireless broadband
WLAN	Wireless local area network
WSN	Wireless network sensors
WTG	Wind turbine generator
WWAN	Wireless wide area network

INTRODUCTION

Over the last two decades digitalisation has been transforming the power sector in a remarkable way. It has helped to reduce the costs of various grid and generation applications, to improve their performance and to multiply environmental benefits for energy consumers.

This transformation has also affected the entire wind energy supply chain, from technology manufacturing to daily operations and dismantling. Figure 1 gives an overview of the expected benefits of digitalisation in the power sector.

FIGURE 1
Potential benefits of digitalisation in the power sector[1].



Key message: Digitalisation in the power sector has the potential to bring benefits to the owners of power sector assets, the wider electricity system, consumers and the environment.

Source: International Energy Agency

1. International Energy Agency, "Digitalisation & Energy", 2017.

Digitalisation is also a key factor in accelerating the electrification of energy demand and the system integration of renewable electricity. According to the European Commission renewables-based electrification will be central to delivering climate neutrality by 2050. To make this happen, wind energy will need to become 50% of the EU's electricity mix with renewables expected to account for over 80%.

The costs of wind energy will continue to decrease thanks to new technologies e.g., rising turbine sizes, capacity factors and optimisation in developing and operating wind farms. The digitalisation of wind farm development, operation and maintenance (O&M) will be a major driver of cost reduction, better performance and lower financial risk.

With that in mind, the wind sector needs to accelerate the momentum of digitalisation. This requires setting common definitions and wind energy digitalisation terminology and metrics. As it stands, universal definitions to describe major digitalisation applications and metrics to assess their benefits are both lacking. For instance, there is no broadly accepted method of collecting, transmitting and reading operational data coming from wind turbines by different Original Equipment Manufacturers (OEMs). Given the lack of standardisation in comparing and analysing information and the increasing complexity of wind farm operations, it is very difficult to compare benefits from different digital applications.

This report **defines major digital applications in wind O&M and a set of digital applications in wind turbine manufacturing and construction.** It also presents the use of generic technologies enabling many of the previous digital applications i.e. big data, 5G technology. For each application, the report lists the potential benefits and challenges but also the technologies that are used today and will be used more over the next decade (Chapter 1, 2 and 3, overview of technical challenges in Annex I).

Secondly, the report **presents several case studies of deployed technologies** showing how digitalisation has transformed the wind sector. Chapter 4 focuses on the **potential of data** in enabling the previous digital applications, notably the need for a universal **wind data standard** and for well-established **data sharing practices**. Considering the current deployment of digital applications and respective technology trends, Chapter 5 lays out our roadmap for the digitalisation of wind energy over the next decade.

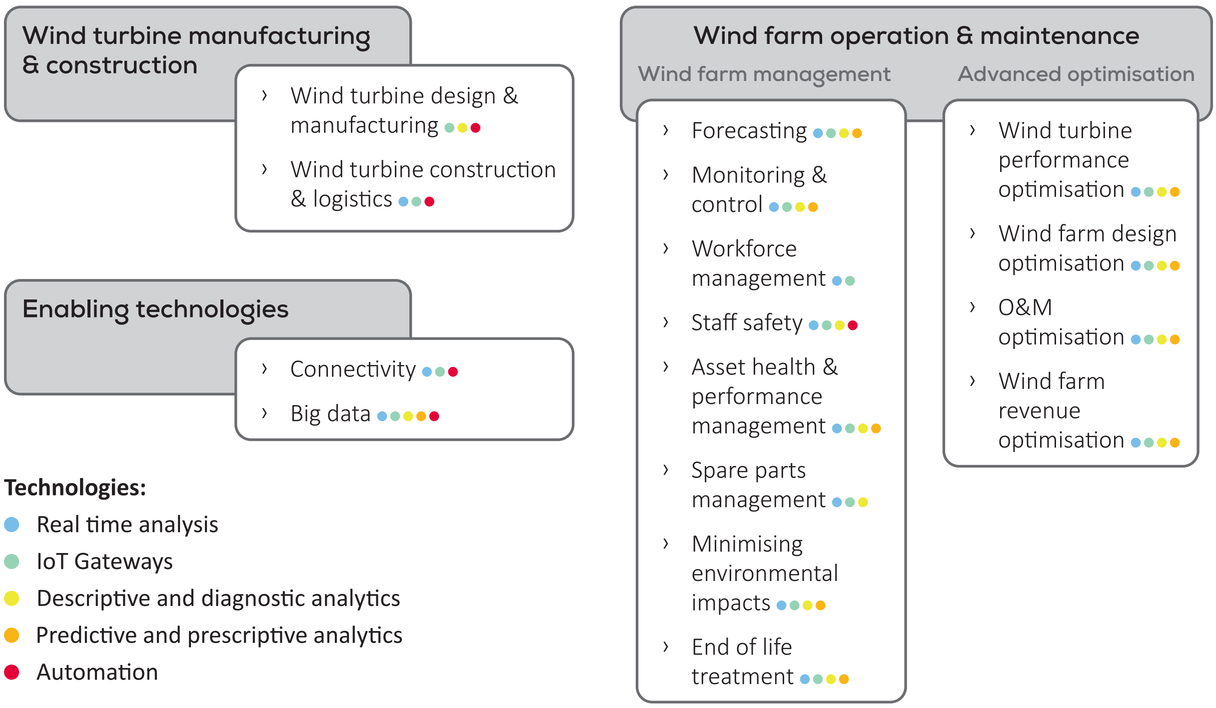
Digitisation is the process of converting information from a physical format into a digital one with the use of dedicated technologies. Over the years the strategies and methods for using digitisation to improve business processes – both digital technologies and data – have led to a new concept that we call **Digitalisation**. Today companies and organisations all over the world have set up digitalisation departments and strategies dedicated to data-driven and automated techniques aimed at increasing efficiency and revenue.

Operation & Maintenance (O&M) in wind energy include all tasks aimed at regularly operating and repairing wind farms or replacing wind turbine components to ensure that wind farms continue to provide expected services across their estimated lifespan.

OVERVIEW OF DIGITAL APPLICATIONS IN WIND ENERGY

Digital applications are deployed to different stages and functionalities of wind generation, from wind turbine manufacturing and construction to system integration and wind farm O&M. Figure 2 illustrates major digital applications in wind farm O&M, wind turbine manufacturing and construction and a set of generic technology applications. It also presents the five main technology categories that we use today in these applications: (a) real time analysis, (b) Internet of Things (IoT) gateways, (c) diagnostic analytics, (d) prescriptive analytics and (e) automation.

FIGURE 2
Digital applications and technologies in wind farm O&M, wind turbine manufacturing and construction and enabling technologies



Source: WindEurope

The five categories of technologies that enable the digitalisation of wind energy today are outlined below:

- **Real time analysis:** Operational processes require a control system to collect, analyse and visualise data obtained from sensing devices that have been installed on critical components. Real time data series of wind, rotational speed, temperature, pressure and various other parameters are being collected and analysed in a centralised computer centre to enhance the control of the wind farm. Supervisory Control and Data Acquisition (SCADA) is the most applied control system in wind farm operation that provides information for real time analysis.

- **IoT gateways:** Wireless broadband (WiBB) is a high-speed internet and data service delivered through a wireless local area network (WLAN) or a wireless wide area network (WWAN). The Internet of Things (IoT) and Industrial IoT (IIoT) provide a reliable connection between different systems and advanced critical communication solutions through the introduction of the 5G network. 5G unleashes the full potential of digital applications in wind.

- **Descriptive and diagnostic analytics:** Descriptive analytics are a statistical method used to search and summarise historical data to identify patterns or meaning. Descriptive analytics provide information on past events. Diagnostic analytics help to identify why something happened in the past. Well-structured data bases and SCADA with historical operational data allow for the development of event and alarm triggers to track system failure[2].

- **Predictive and prescriptive analytics:** A set of statistics and data modelling techniques usually based on machine learning (ML) and artificial intelligence (AI) algorithms use historical data to forecast wind turbine outcome and performance results. With the ongoing shift to AI-based solutions, industry is beginning to take predictive analytics one step further towards a proactive approach[3] based on real time data monitoring and event analysis both to prevent incidents or adjust conditions before a critical moment.

- **Automation:** Robotic process automation (RPA) is a process-driven method which instructs machines on how to replicate human-directed tasks. This technology can improve manufacturing accuracy, reduce human error and accelerate repetitive industrial operations.

Figure 3 presents commonly used tools that are included today in each of the above categories.

FIGURE 3
Technology categories and tools used today for the digitalisation of wind energy

Technology categories and tools in wind energy digitalisation

Real time analysis
- SCADA
- Aeroelastic simulations
- Climate analysis software
- Cloud analytics
- Robust controllers
- Digital supply chain

IoT Gateways
- Cloud services
- Remote sensing
- Edge computing
- Augmented reality
- Broadband networks(LTE/5G)
- Cellular IoT

Diagnostic and descriptive analytics
- SCADA
- Digital twin
- Root cause analysis
- Condition monitoring
- Computerised maintenance management system (CMMS)
- Building information model

Predictive and prescriptive analytics
- Machine learning
- Artificial intelligence
- Supply chain platforms
- Trading platforms
- Digital twin
- Digital supply chain

Automation
- Autonomous vessels
- Artificial intelligence
- 3D printing
- Digital twin
- Laser/ultrasonic
- Robotics
- Digital supply chain

Source: WindEurope

2. Sigma Computing, Descriptive, Predictive, Prescriptive and Diagnostic Analytics: A Quick Guide
3. Techsling, From Reactive To Proactive Analytics, July 2020

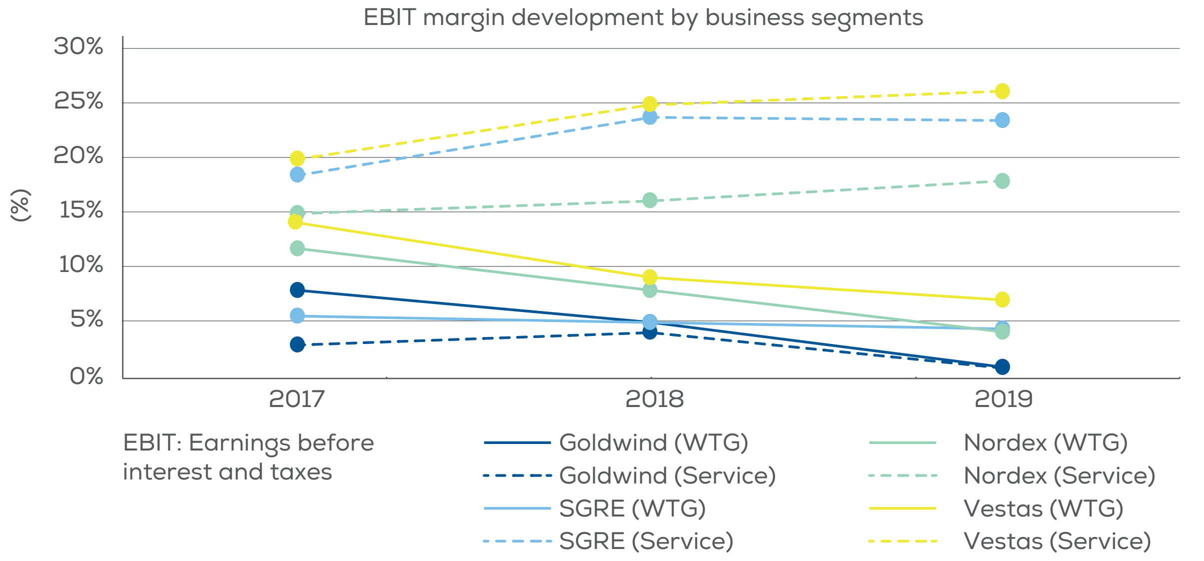
1. DIGITALISATION IN WIND FARM OPERATION & MAINTENANCE

Wind farm O&M today represents anything from 25% to more than 35% of the overall LCOE of wind energy[4]. Over the next few decades important O&M cost reductions are expected across all technologies (a 5% reduction of LCOE in onshore, 8% in bottom-fixed offshore and 13% in floating offshore)[5]. Wind farm O&M service contracts – enabled mainly through digitalisation – and optimised asset management practices will play a key role in this. Unplanned turbine maintenance represents two thirds of total wind farm OPEX on average and full data access could lead to significant reductions here[6,7].

Today O&M self-servicing (O&M service contracts under which a wind turbine or component OEM undertakes the O&M service of its own equipment on behalf of the asset owner) is already an important factor in wind turbine manufacturing revenue and this trend seems to be increasing as presented in Figure 4. In terms of capacity, 70% to 80% of the wind turbines that have been ordered in 2020 in Europe include an O&M contract between the wind turbine OEM and the wind farm owner[8].

4. The LCOE of wind is driven by five primary parameters: upfront capital expenditures (CAPEX), operational expenditures (OPEX), project performance, financing and tax assumptions and project life. Source: Wiser, Ryan, Bolinger, Mark and Lantz, Eric J., "Assessing wind power operating costs in the United States: Results from a survey of wind industry experts'', 2019
5. ETIP Wind, WindEurope, "Getting fit for 55 and set for 2050", June 2021
6. A recent case study in an onshore wind farm concluded that digitising O&M with full access to available data offered a benefit of 1.2m$ for 114 turbines. Source: Onyx Insight, "Data Access: Thinking about tomorrow", October 2020.
7. Press release: Wood Mackenzie, Unplanned wind turbine repairs to cost industry $8 billion + in 2019, June 2019
8. WindEurope, "Wind Turbine Orders Monitoring", 2021

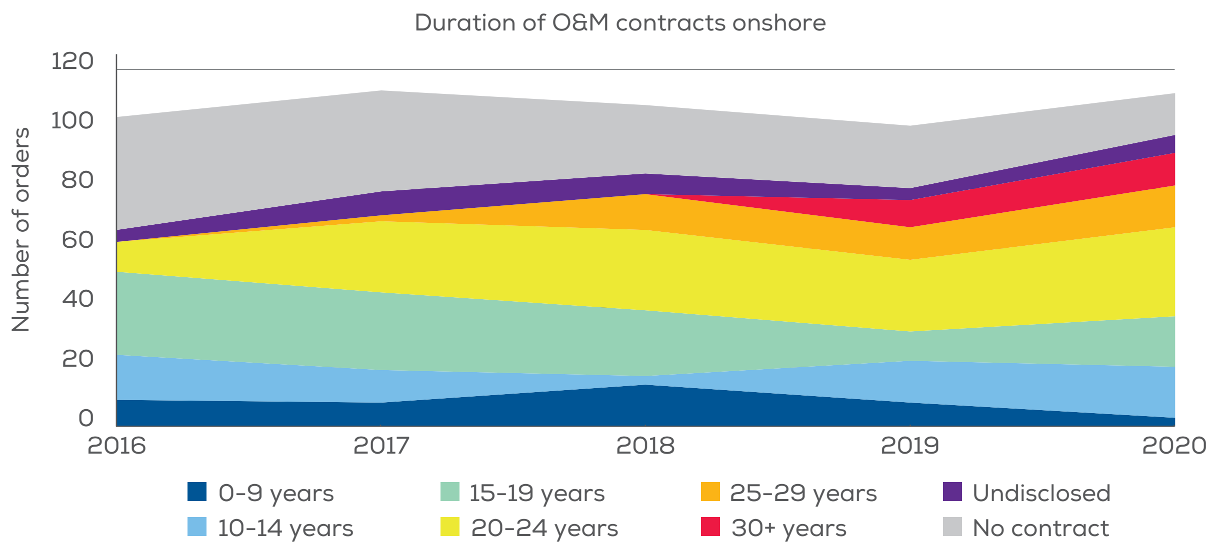
FIGURE 4
EBIT margin development by wind turbine manufacturer business segment



Source: Wood Mackenzie

Moreover, wind O&M contracts today are lasting longer than before. Whereas in 2016 most contracts for onshore wind farms covered less than 20 years, in 2020 over half of them went beyond 20 years, with a growing share reaching up to 30 years. Figure 5 shows the duration of O&M contracts that have been integrated in wind turbine orders in the period between 2016 and 2020 in Europe.

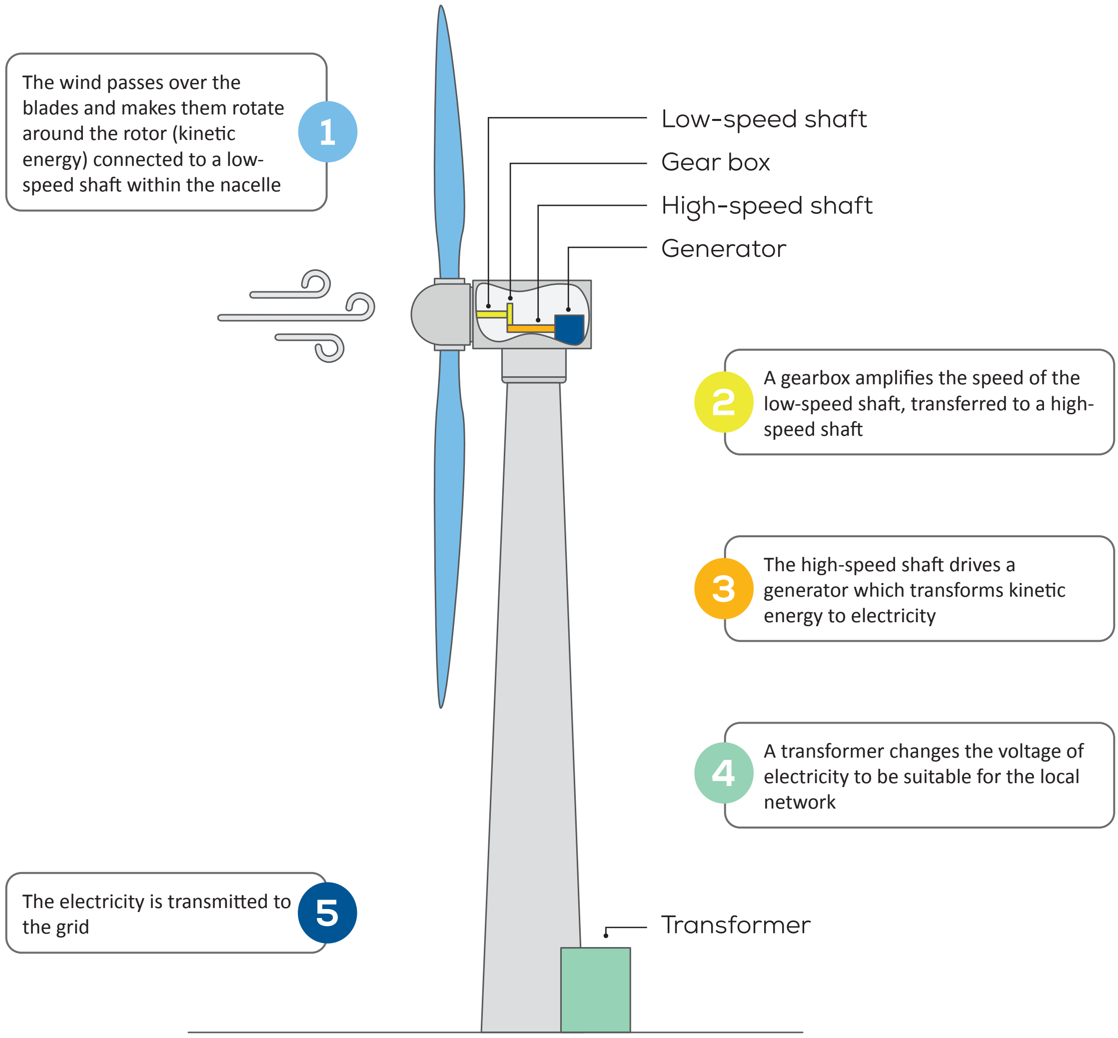
FIGURE 5
Duration of O&M contracts integrated in wind turbine orders 2016 – 2020



Source: WindEurope

For all these reasons, this report looks at major digital applications that can lead to more O&M cost reduction and further guarantees of wind farm reliability. These applications facilitate all operational steps of wind energy generation illustrated in Figure 6: (1) blade rotation, (2) motion of components in the nacelle, (3) electricity generation, (4) conversion of electricity to local grid parameters, (5) export of electricity to the grid. They also facilitate the maintenance of wind turbines and their components.

FIGURE 6
Wind energy generation steps



Source: Wind Europe

1.1 WIND FARM MANAGEMENT

FORECASTING

TECHNOLOGIES AND BENEFITS

Wind power forecasting is the process of estimating the expected output from one or more wind turbines. Data-oriented platforms collect weather data and climate conditions from sensors placed onsite and relate them with energy output patterns, based on AI technology and statistical distribution models.

Forecasting time scales vary according to the required output. Immediate forecasting, lasting up to several minutes, serves as an efficient turbine active control, while short-term forecasting enables optimisation methods for power output and energy trading strategies over the next 24 to 72 hours. Long-term forecasting helps with maintenance scheduling and transmission stability up to a week ahead of time.

Classifying forecasting methods depends on data source and data manipulation approaches. The two main methods are physical and statistical:

- The physical approach is based on numerical and mathematical meteorological forecasting with the use of data collected at different locations close to site.
- The statistical approach relies on historical meteorological data and wind power variables to predict new parametrical models.

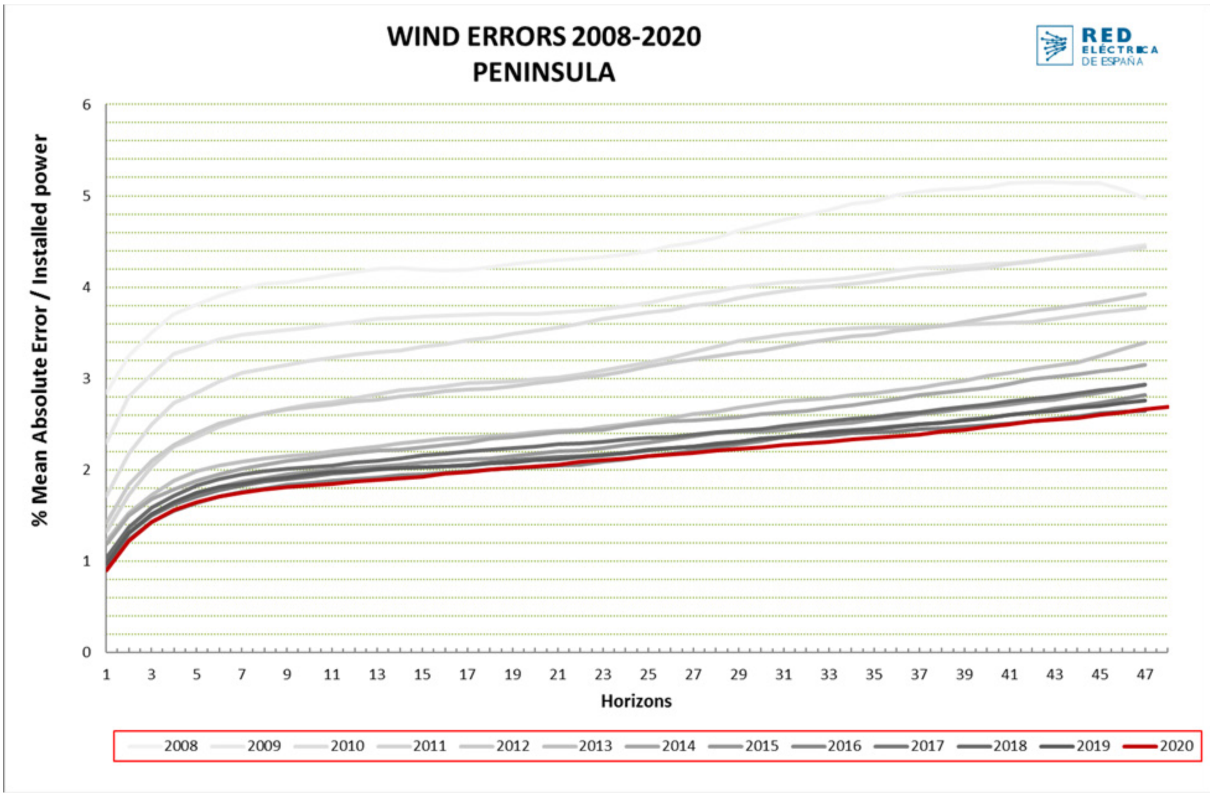
A combination of both models allows for more comprehensive and refined modelling of weather condition parameters, better support for the system to balance demand and supply and an efficient predictive maintenance scheduling. Figure 7 shows how the forecast accuracy of wind power production (as the ratio of the mean absolute error to the total installed wind power) has improved between 2008 and 2020 in Spain thanks to evolution of forecasting methodologies and tools.

CHALLENGES AND BARRIERS

Current AI and deep learning models allow for more accurate forecasting – nevertheless, uncertainty remains high. The stochastic nature of atmospheric weather parameters and shifts in wind turbine controller technology create the need for ongoing verification of forecasting models. In the offshore case forecasting accuracy remains a challenge – wind and wave conditions are not globally charted while an unstable structural response against loading can lead to sub-optimal performance control. Further research and modelling validation will be needed to improve the quality of offshore wind forecasting[9,10].

9. J. Manero, J. Bejar, U. Cortes, Wind Energy Forecasting with Neural Networks, 2018
10. H. Liu, C. Chen, X. Lv, X. Wu, M. Liu, Deterministic wind energy forecasting, A review of intelligent predictors and auxiliary methods, Energy Conversion and Management, 2019

FIGURE 7
Wind power production forecast accuracy improvement in Spain[11]



Source: REE

11. IEA Wind TCP Task 25, "Final summary report: Design and operation of energy systems with large amounts of variable generation", 2021

CASE STUDIES

Below we present two case studies of digital applications in wind power forecasting: (1) forecasting of wind farm ice loss and ice risk at several wind farms in Norway and (2) big data for wind power forecasting in a large wind farm fleet.

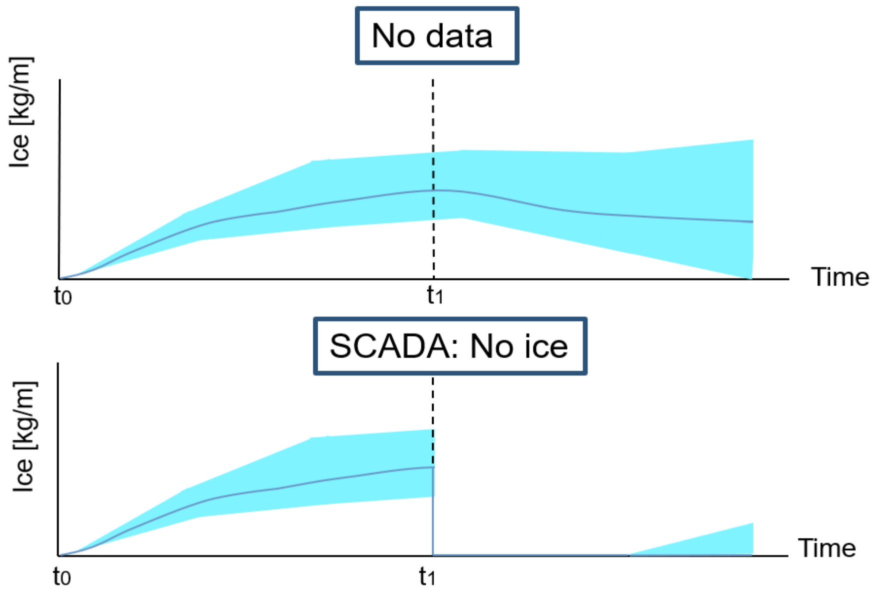
Forecasting wind farm ice loss and ice risk

OPERATOR:
Various

SOLUTION PROVIDER:
Kjeller Vindteknikk

OBJECTIVE:
Using real-time SCADA data to perform running calibrations of the ice prediction model, improving both the nowcast and the forecast

IceRiskForecast is an icing forecast model for wind farm applications[12]. The model has been tested at several wind farms in Norway and Sweden and is currently being used at Fosen Vind (Statkraft), Guleslettene and Kvitfjell/Raudfjell (Zephyr), Ånstadblåheia (Fortum), Tonstad (Hydro) and Fäbodliden (Fred Olsen) among others. The basis of the icing forecast model consists of numerical weather prediction models together with wind and production data from the wind farm. For the shortest forecasts (1 to 6 hours), real-time production data from the wind farm are used. The forecasts provide hourly information about ice risk and ice loss for the upcoming 36 or 48 hours. The system may also be used for probabilistic production forecasts. The forecast is updated four times daily and can be calibrated for the site and combined with onsite measurements where needed.



Running calibration of the probabilistic forecast

12. K.Ingvaldsen, S.Grini, B. E.Nygaard, Combining ensemble forecasts with real-time SCADA data to increase the reliability of ice loss and ice risk forecasts, WindEurope Technology Workshop 2021

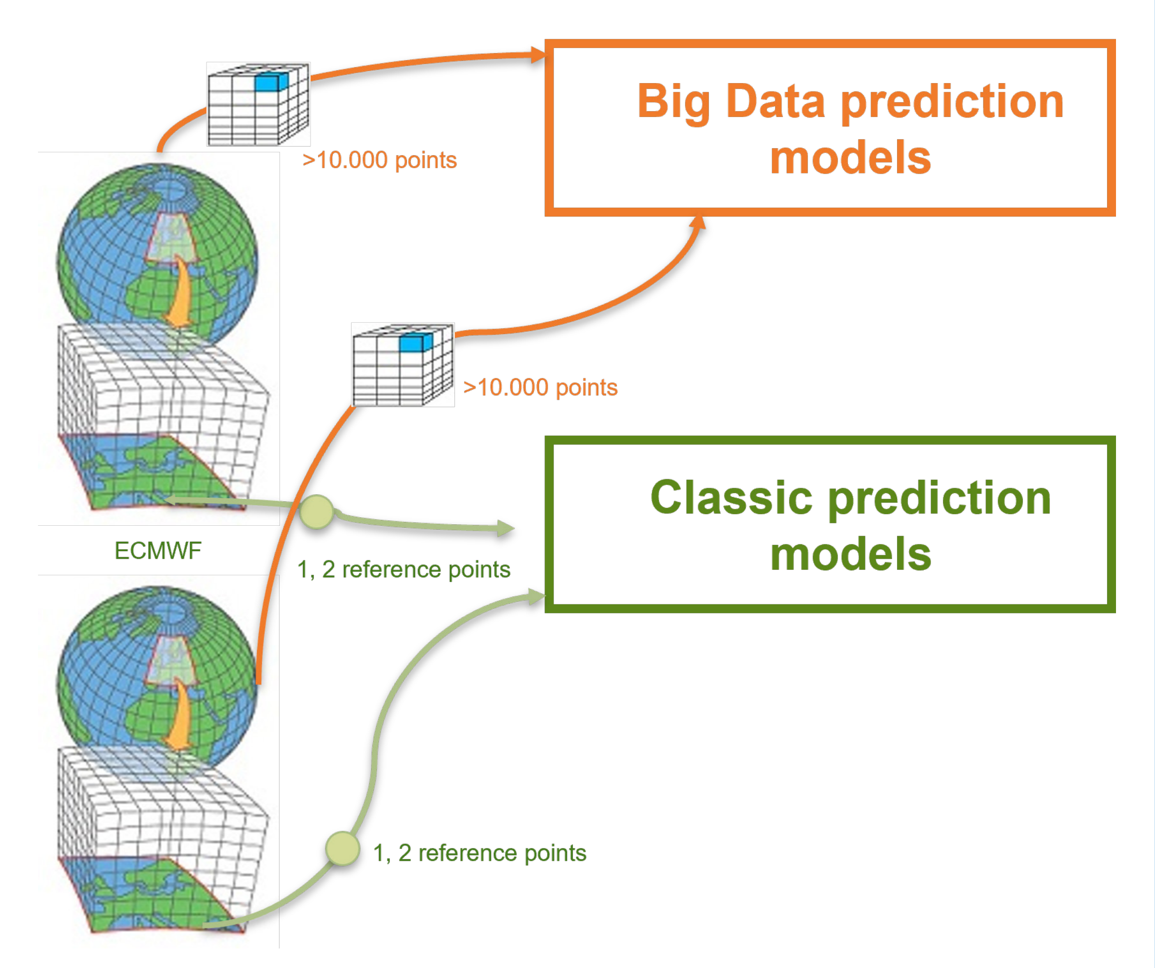
Big data for wind power forecasting

OPERATOR:
Iberdrola

SOLUTION PROVIDER:
Instituto de ingeniería del conocimiento (IIC)

OBJECTIVE:
Using big data technology to generate prediction models accounting for all meteorological parameters within a radius of tens of kilometres that might influence wind farm power generation

Standard prediction models combine global meteorological models of three-dimensional arrays (e.g. from the European Centre for Medium-Range Weather Forecast or the Global Forecast System) with weather condition data from the reference points of the wind farm and historical performance data to predict potential power output. Big data technology simultaneously uses data from the three-dimensional array models covering an area of several kilometres around the wind farm. This leads to more reliable predictions of the wind farm's power outcome. However, it also calls for greater data storage capacity and post processing of data. This includes filtering variables that influence the prediction of the farm output as well as the operation of the prediction models when accounting for the selected variables.



MONITORING AND CONTROL

TECHNOLOGIES AND BENEFITS

Advanced sensing devices can collect information about many parameters related to the operation and condition of a wind farm, substructures and individual turbine components. The exported information ends up on cloud-based wind monitoring platforms for inspection and further analysis. These platforms are in most cases supervisory control and data acquisition (SCADA) networks. Figure 8 gives an overview of typical monitoring and communication systems in a wind farm.

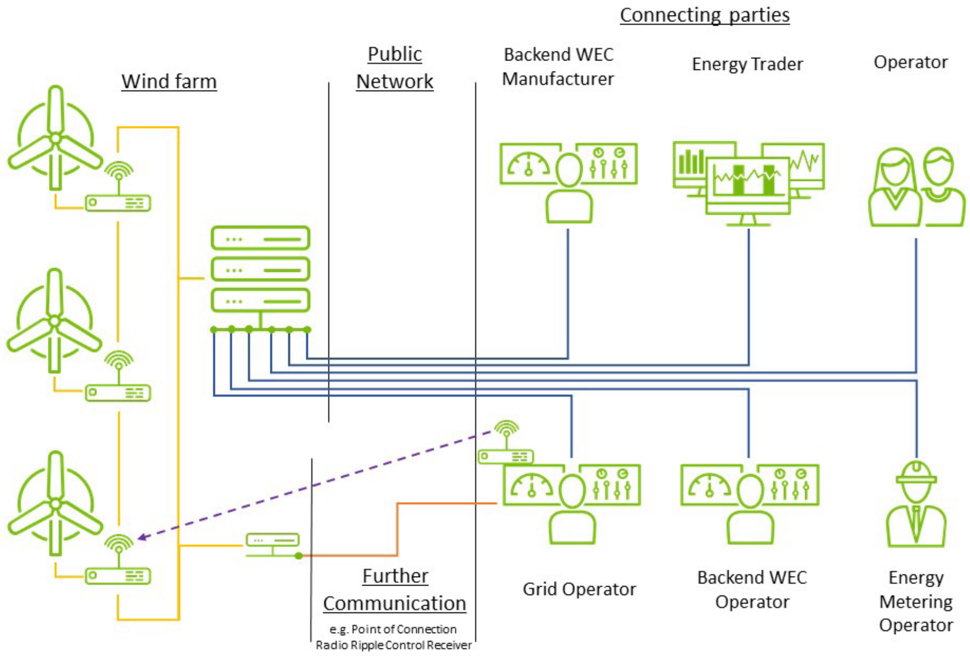
Common parameters of interest are wind speed and direction, rotational speed, temperatures, pressure, voltage and current level – all of which directly affect turbine performance and power output. This data is used to construct data learning curves to detect abnormal behaviors, based on mathematical and statistical modelling, while optimisation models are used to schedule predictive and preventive maintenance and manage the wind energy fleet.

Learning curves provide the ability to optimise corrective actions on different sections, such as maintenance schedule, spare part management and work force mobilisation. Further manipulation of collected monitoring data support root cause analysis (RCA) evaluation over damaged turbines and subcomponents. Real-time performance monitoring allows alarm triggering to prevent any potential failure of critical components. Early damage due to icing and erosion on blades and corrosion of metallic parts can be detected early through advanced sensing devices and prediction models can estimate potential failures.

This valuable information can lead to the development of predictive and preventive maintenance strategies which help to reduce time and cost. Additional monitoring can be used to detect birds and bats approaching rotating blades and avoiding collisions. The value of these information lead to development of predictive and preventive maintenance strategies, saving valuable time and reducing significantly O&M expenses.

FIGURE 8

Overview of typical monitoring and communication systems in a wind farm[13]



WEC: Wind energy converter

Source: BWE

13. BWE, "Orientierungshilfe Informationssicherheit Wind", April 2021

CHALLENGES AND BARRIERS

The large diversity of turbine models, the high number of active critical components during the operation of the wind farm and the unique material properties strengthen the need for advanced SCADA systems, able to combine variables from different sources, manufacturing and operating data onto a single-level platform. The presence of wind technology experts in the control room is vital to encourage critical analysis of system imperfections, eventually leading to monitoring improvements.

Moreover, the statistical distributions used in ML and AI models need to be constantly verified with real conditions and updates. Finally, the lack of a universal data standard leads to customised solutions and time-consuming processes.

CASE STUDIES

The next four case studies present digital applications in wind farm monitoring and control: (1) an O&M platform for Rentel, Seastar and Mermaid wind farms in Belgium, (2) a fault handling automation solution for 763 wind turbines in Spain, (3) a monitoring and control centre for an international wind farm fleet and (4) a health index monitoring solution for wind farm transformers.

O&M platform for Rentel, Seastar and Mermaid wind farms

OPERATOR:
Otary Group

SOLUTION PROVIDER:
e-BO Enterprises

OBJECTIVE:
Digital O&M platform, combining operations and data and engaging with all stakeholders involved in offshore wind farm maintenance

The project aims to maintain more than 100 offshore assets (including 3 offshore substations), all observations directly made within the e-Wind system. Maintenance operations are tracked and integrated with all available data, collected from wind turbine generator (WTG)/ offshore high-voltage substation (OHVS) SCADA and other relevant systems like weather forecasts, CMS and distributed temperature sensing (DTS). Maintenance teams are informed and review them to schedule and plan work orders and permits. During works or inspections, the system not only registers the activity itself but also links it to the potential loss of production and to perform critical operations safely (such as isolations) and tracking of goods and personnel. After the work is complete, the owner has in possession both a full track-record of maintenance activities and site accesses, they will also be able to link the activities with the SCADA alerts using live data trending to enrich their findings. Importantly, maintenance processes within the project are well-defined but also adaptable. All stakeholders have been granted access to the system with respect to GDPR and the occasionally complex organisational structure they are working in.

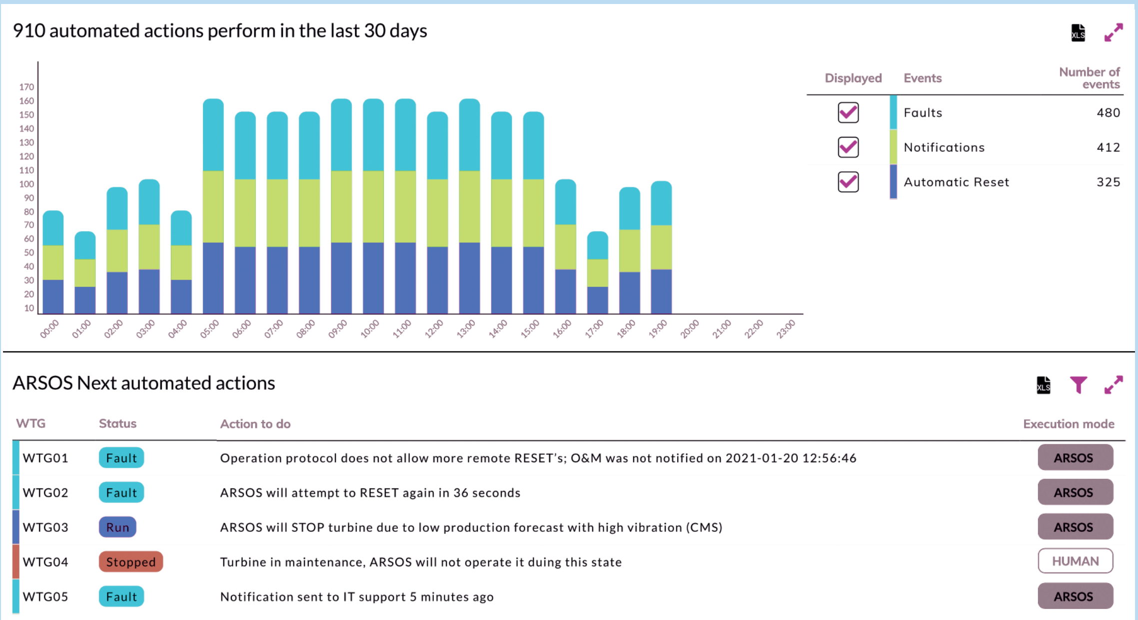
Fault handling automation

OPERATOR:
RWE

SOLUTION PROVIDER:
Green Eagle Solutions

OBJECTIVE:
Automation of Iberian RWE's fault handling procedure to improve operational efficiency

The Remote operations centre (ROC) of RWE Renewable Iberia has installed ARSOS, an intelligent control software designed to autonomously operate its 763 wind turbines across Spain and Italy. Typically, a control centre team monitors incoming data from the turbines for any complications and workers check and determine if restart or onsite maintenance is needed, which takes 15-30 minutes on average. In a portfolio of 1,000 turbines, this could mean 12,000 hours of aggregated unavailability and production loss. ARSOS allows for the automation of operations protocol with AI algorithms to automate smart operations – cutting turbine downtime and operational costs while maximising availability and revenue. Thanks to this, response time has been reduced to almost zero and operation capabilities have doubled. Moreover, the implementation of preventive stops has reduced yearly costs of O&M thanks to the optimisation of major repairs. In just one month, at a single RWE wind farm, ARSOS executed 910 automated actions, 600 turbine resets and 300 notifications informing field technicians of onsite issues that needed fixing. RWE estimates that ARSOS could optimise and potentially save around 1,400 hours of work, or a minimum of €110,000 a year.



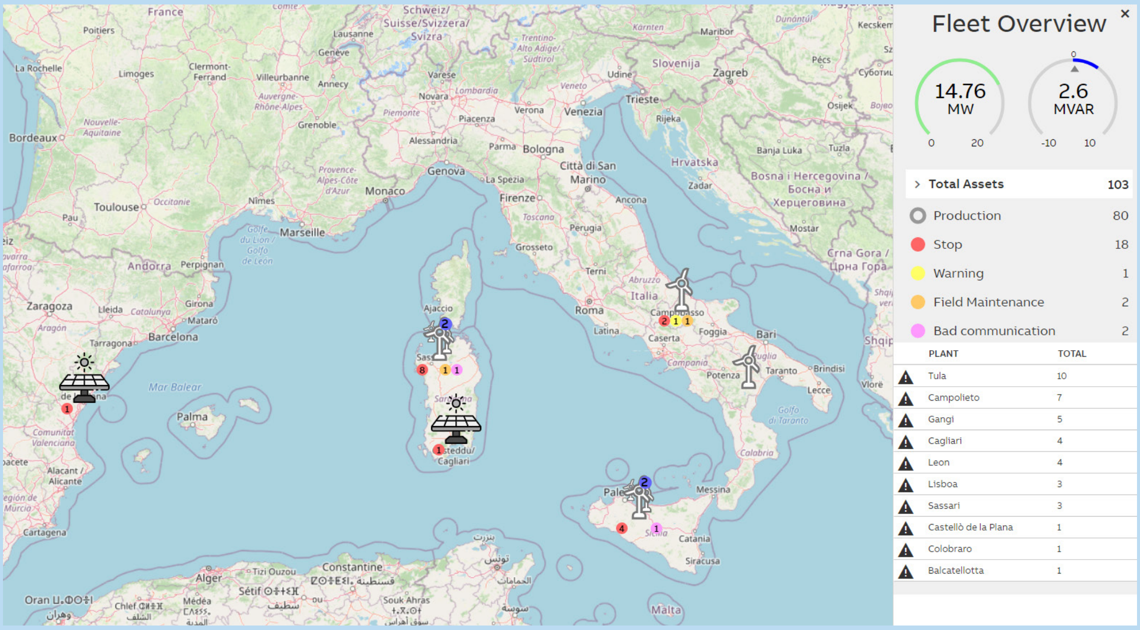
Monitoring and control centre for a wind farm fleet

OPERATOR:
Not public information

SOLUTION PROVIDER:
Hitachi Energy

OBJECTIVE:
Updating an inefficient, outdated and non-cybersecure system with a new, cost-effective monitoring and control centre integrating wind, solar and virtual power plant (VPP) assets into one single solution.

SCADA solution with local gateways collecting information from the field and making it available for top-level monitoring and controls for solar, wind and virtual power plants. The solution offers modernisation of remote control centre (RCC) to MicroSCADA X RCC and enables the expansion of the monitored fleet. The reaction time is improved through structuring and visualisation of critical data in a high-level display. The operational cost is reduced by managing all assets through a fully integrated automation system. The tool is also compliant with customer cyber-security requirements.



Wind farm transformer health index monitoring

OPERATOR:
Not public information

SOLUTION PROVIDER:
Cognite

OBJECTIVE:
Reducing wind farm transformer failure rates and replacement and repair cost

Power transformers are critical components for any wind farm as well as the entire power grid. Any malfunction is costly, leading to a loss of revenue as well as replacement costs. From the perspective of both a wind farm operator as well as a Transmission System Operator (TSO), it is vital to better leverage data to help identify early signs of transformer failure and then optimise its spending on replacement parts. The respective TSO has worked with an industrial data operations provider to free information about transformers from its source systems, including temperature, load, dissolved gas analysis, technical specifications and inspection logs and feed it into a data fusion platform. With access to all the data relevant to transformers in a single location, the development team was able to calculate a health index for every transformer. This health index was then visualised on a dashboard, giving the grid operator engineers the ability to monitor the entire fleet of transformers briefly and see which components should be prioritised for maintenance. Now that the operator can make smarter, data-driven decisions, they have been able to save $2m per year while reducing the failure rate by more than 20%.

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WORKFORCE MANAGEMENT

TECHNOLOGIES AND BENEFITS

Workforce management includes all applications that support wind O&M technicians and managers in planning and managing the various O&M activities, permits-to-work, personal qualifications and associated business processes i.e. payroll and real time project costing monitoring. Another major objective of workforce management is to ensure health and safety. Today these tasks can be optimised with digital platforms enabling remote working, real time tracking of activities, workforce certification management, critical communications for health and safety, multi-network dispatchers and other applications.

Benefits include improved staff well-being and health and safety, standardised real-time scheduling of activities across sites, reduced waiting time between assignments, enhanced routine maintenance and increased predictability. These tools for digital workforce management can be applied to all organisations and industries that have a contact centre and a geographically dispersed field resource.

CHALLENGES AND BARRIERS

Different health and safety needs, payroll regulations, taxing and insurance systems across countries and continents can limit the efficiency of workforce management software. Customising such data-drive platforms raises the cost of the application and the need for continuous updates.

CASE STUDIES

Below we present the application of a digital service supporting the mobility of 800 workers in wind farms located in 15 countries.

Advanced service for staff mobility in wind farms

DEVELOPER:
EDPR

SOLUTION PROVIDER:
Atos

OBJECTIVE:
A rapid, comprehensive cloud-based platform for 800 windfarm workers in 15 countries

Atos deployed Microsoft Dynamics 365 Field Service as part of an integrated cost-efficient approach that also made use of EDPR existing enterprise systems. The solution is configurable to support different kinds of assets at each wind farm as well as EDPR's three existing SAP-modules – SAP Plant Maintenance (SAP PM), Materials Management (SAP MM) and Warehouse Management (SAP WM). This is designed so that activities and work orders related to the management of materials and warehouses could be orchestrated from the mobile platform. The new platform has been implemented in 350 wind farms covering 6,500 wind turbines of different types. Thanks to this deployment technicians can access and process information in the field, at the office or on the move and update it in real time. Business functions, processes and locations can be added and changed quickly and easily. The solution has improved control of field activities by 25% and contributed to EDPR's sustainability goal of reducing emissions from unnecessary travel to the field.

STAFF SAFETY

TECHNOLOGIES AND BENEFITS

Wind farm technicians are often required to carry out physical inspections of wind turbine towers and blades exposing themselves to extreme wind and wave conditions in the process. Digital tools reduce the risk of accident through alarm triggers and improve the response for emergencies and when we need to rescue people.

Simulations on virtual training platforms make workers familiar with the turbine structure as well as the location and uses of the mechanical equipment. Thanks to virtual reality tools wind turbine technicians have the chance to experience maintenance procedures several times before they have to do it for real. Advanced connectivity solutions also allow for stable real-time voice and video communication among technicians and managers using mobile spectrum radio devices and scene cameras.

This can help prevent accidents by automatically locating those people who are working in the high-risk areas. Remote blade inspection with integrated systems such as drones, thermal-imaging cameras and advanced sensing of mechanical equipment can also offer alternatives to physical supervision.

CHALLENGES AND BARRIERS

Bringing these applications from offshore to onshore through remote inspection involves regular hardware and software updates and qualified staff to control these updates. Radio devices and equipment should be able to support new communication technologies which is often not the case in legacy systems. Remote failure detection requires staff with highly technical background to secure reliable predictions.

Failure alarm triggers, developed through SCADA systems, bring several turbine and grid performance parameters together so their efficiency heavily depends on the quality of the collected data. Moreover, the lack of standard failure protocols and integrated monitoring systems limits the wide uptake of remote inspections and digital tools for staff safety[14].

CASE STUDIES

The following case study presents a digital central platform supporting safe operations in an offshore wind farm fleet in Belgium.

Central platform for safe offshore operations

DEVELOPER:
Parkwind NV

SOLUTION PROVIDER:
e-BO Enterprises

OBJECTIVE:
Safer offshore operations through digitalisation, integration and collaboration

This project started in 2014 and includes delivery of a central software platform making offshore operations safer, meeting all regulatory requirements and reducing operational and administration work by engaging people to jointly work from the same system/data. The platform is used by many workers to register and follow the necessary inductions to get access to the sites and the necessary qualifications defined within the system. Furthermore, it is used to keep track of offshore operations and to register, review and approve transfers and tasks. It also tracks vessel and staff positions. Combined with additional sources of information like automatic identification system (AIS), closed-circuit television (CCTV), radar and meteorological data, a shared geographical information system (GIS)-supported picture is created and shared with all relevant stakeholders. Also central to the system - and available to all - are notifications and observations. Supported by additional media, attachments and chat functionalities, the asset and QHSSE managers within Parkwind can directly follow up and take further action such as assigning necessary tasks, reporting to Governments, issuing safety notices and other. Recently the project has moved onto inventory management of safety-related materials by tracking and assigning them and following up with inspections, making the process paperless and giving the worker more control.

14. McKinsey & Company, A safer, smarter future: Working remotely in energy and materials, May 2020

ASSET HEALTH AND PERFORMANCE MANAGEMENT

TECHNOLOGIES AND BENEFITS

To achieve efficient performance and operation, digital platforms for wind asset management bring together different tools for monitoring and site inspection, power curve analysis and market participation, an inventory of critical components and tools for the communication of managers, technicians and operators.

These tools perform data analysis often based on AI, classify maintenance tasks in function of criticality and cost and provide a standard procedure for connecting systems, data and people to deliver faster time-to-market.

CHALLENGES AND BARRIERS

Developing such digital platforms that can provide full coverage and transparency while minimising the number of required interfaces requires deep technical understanding and market insight. Moreover, the current O&M servicing framework involves several parties with different data ownership. This makes difficult the exchange of knowledge gained through different operational channels. High implementation cost in time and money is another barrier to the wide use of such tools. Their transferability to different contexts and turbine models will become more cost-effective when the sector will establish data sharing practices.

CASE STUDIES

Below we present three case studies of digital applications in asset health and performance management: (1) an international monitoring and analysis platform at wind farm fleet, wind farm and machine level, (2) a long-term performance assessment tool deployed at several wind turbines in Italy and in the UK and (3) a technical and financial underperformance analysis tool used at several wind farms internationally.

Engie DARWIN

DEVELOPER:
Engie

SOLUTION PROVIDER:
Engie

OBJECTIVE:
Monitor and analyse assets at fleet, wind farm and machine level

This solution collects wind, solar, hydroelectric and biogas asset data which is cross-checked with other information, like meta-data, weather forecasts and digital twin data from Darwin algorithms. This allows to perform custom reporting and analysis of data at fleet, asset, or turbine level, up to a 10-min granularity. Additionally, it provides the ability to integrate with business intelligence tools and gives access to main Key Performance Indicators (KPIs). It also supports predefined root cause analysis in conjunction with alert triggers. Furthermore, DARWIN can be linked to the aggregators' and off-takers market, using the curtailment API to curtail assets when intraday prices are negative, as real-time APIs compute the day-ahead and intraday nominations. Today the DARWIN platform supports monitoring, analysis and reporting of 21GW of assets on heterogeneous SCADA-systems, on a 24/7 basis, located in 25 countries globally.

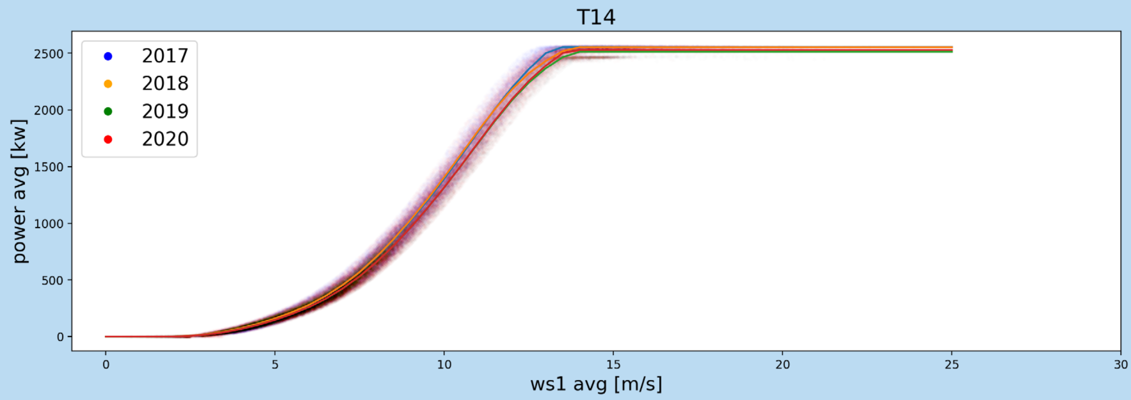
Long-term wind turbine performance assessment

OPERATOR:
Falck Renewables

SOLUTION PROVIDER:
NUO

OBJECTIVE:
Fault prediction for several wind turbine components simultaneously using ML & AI techniques, allowing an adaptive and scalable system localisation of faults.

Falck Renewables developed a novel framework for assessing wind turbine performance deterioration with age through a data-driven approach, to help improve their life management and financial return. The aim is to identify turbines showing higher levels of performance deterioration and prioritise them for further offsite and onsite analysis. The performance assessment framework to be used here has been tested on various sites in the UK and Italy, featuring modern multi-MW wind turbines over the same reference period. The results show that the two analysis techniques that were used (i.e., traditional power curve assessment and ML-based model) predict a similar rate of turbine performance deterioration across all the wind turbines (~1% per year), with some assets experiencing significantly higher average deterioration (>5% per year) over the reference period.



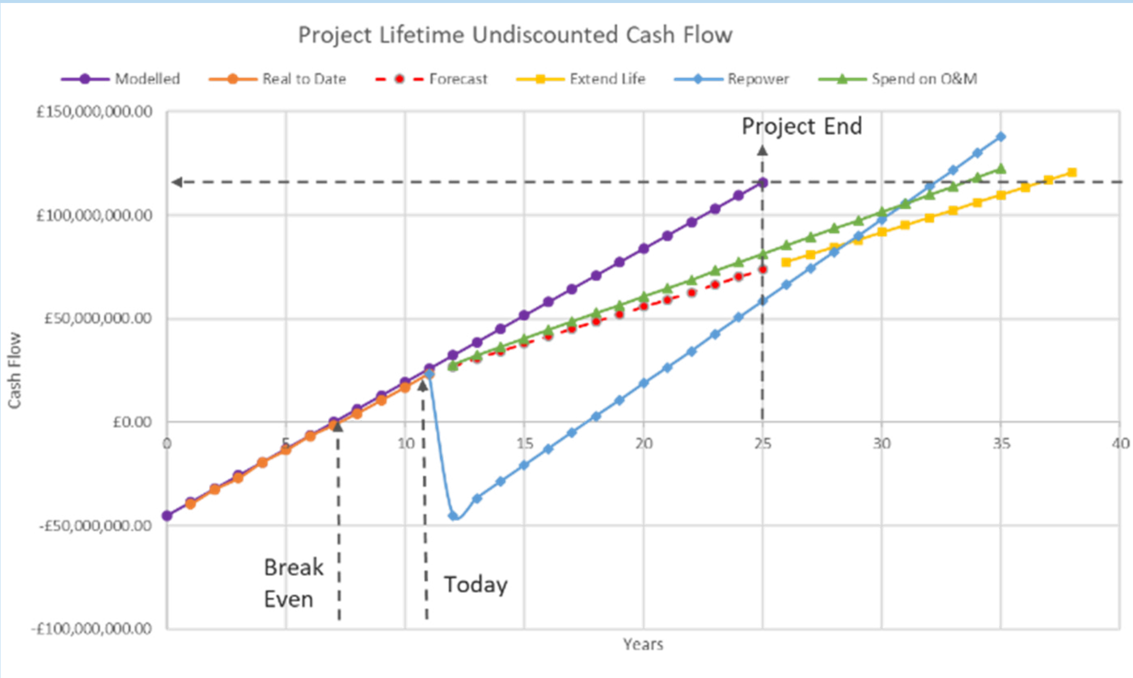
Exceedence COMPARE underperformance analysis

DEVELOPER:
Exceedence Finance Ltd.

SOLUTION PROVIDER:
Exceedence Finance Ltd.

OBJECTIVE:
Identifying systematic underperformance of assets based on expected and actual wind farm operation data

This tool offers a holistic solution that builds a digital twin from a technical and financial performance approach. Key figures include monthly yield, revenue, internal rate of return (IRR), net present value (NPV) and LCOE data. A series of comparisons over time allow for analysis on a farm or turbine level. The project examines an operating farm made up of nine turbines with an installed capacity of 22.5MW. The portfolio dashboard highlights the underperforming components. The modelled output shows what was originally forecast in the techno-financial model and compares it with the actual wind data. A single turbine and farm asset underperformance can be reviewed, comparing relevant KPIs. The software looks at several possible scenarios based on actions that the farm owner could take. These scenarios examine the current state of the farm, potential lifetime extension, O&M strategy configuration or possible repowering.



SPARE PARTS MANAGEMENT

TECHNOLOGIES AND BENEFITS

Failures are scattered over different parts of the wind turbines but occur most frequently in the electrical system, the hydraulics and control system, the sensors, the blades and the gearbox. The blades and gears benefit the most from spare parts management since they are usually not repaired but directly replaced. Digital spare part management tools can improve the balance between supply and demand of these items and allow for reactive and scheduled maintenance.

Automated techniques can improve material replenishment and significantly cut the cost of logistics and inventory holdings. The development of a global digital marketplace for used components will lead to a drop in equipment prices, as the available stock will grow. Equipment exchanges and re-use will strengthen the deployment of Quality Computerised Maintenance Management Systems (CMMS) on the energy market, offering concrete knowledge of materials quality and fatigue resistance and optimising maintenance techniques.

CHALLENGES AND BARRIERS

Digital spare parts management requires the deployment of advanced inventory management tools to calculate ideal inventory levels across the network of spare part distribution centres. It also requires the storing and manipulation of huge volumes of data. Moreover, the continuous update of the tools with field data – not easily accessible - is vital to train AI models for parts failure and demand forecasting.

Further to these, aligning spare parts management with business goals and Key Performance Indicators (KPIs) is not an easy task. Finally, digital spare parts management also requires qualified staff to identify the criticality of different parts and estimate overall costs. Despite these drawbacks, the deployment of digital spare part management tools has shown encouraging signs in the wind industry[15].

CASE STUDIES

The following case study presents an optimisation platform for spare parts management in an international fleet of wind farms.

Spare parts optimisation

OPERATOR:
Various

SOLUTION PROVIDER:
ZF Wind Power

OBJECTIVE:
Support wind turbine operators and fleet owners to optimise the spare parts inventory planning and enable lifetime extensions

The lead time to repair wind turbine gearboxes strongly depends on the actual stock of spare parts. If spare parts are readily available, a gearbox critical failure can still take up to four weeks to be resolved due to time needed for investigation, field inspection, parts order, planning and repair. Such downtime would lead to €50K in revenue losses for a 3.5MW turbine. If spare parts are not readily available this period is significantly prolonged. ZF has developed a platform that combines various data sources and analytical models to improve the availability of spare parts. The model merges field data with the gearbox digital birth certificate to calculate the age of the gearbox at a main component level. This overview allows asset owners and operators to investigate lifetime extensions on each gearbox. Additionally, service intervention history and operating information are used to deploy ZF analytics model and make reliable statistical fleet predictions on remaining lifetime. The output is collected and visualised on a dashboard showing which spare parts will be needed on an asset basis in the coming years.

15. ORE Catapult, "Spare parts management in offshore wind", June 2017 ORE Catapult, "Spare parts management in offshore wind", June 2017

MINIMISING ENVIRONMENTAL IMPACTS

TECHNOLOGIES AND BENEFITS

Digital solutions are used for the environmental impact assessment of wind farms and for the prevention of unpredictable wildlife disturbances. Tools based on geographic information system (GIS) analysis carry out preliminary landscape reviews and a visualisation of the existing and proposed wind farm locations, onshore and offshore. The exported datasets account for several influencing factors on a map including wind status, the use of land, existing grid infrastructure and road access.

New image processing technologies, applied in cameras as the one shown in Figure 9, can detect approaching birds and bats, and can pause blade rotation to avoid a potential collision. This is achieved by sending out sound signals for birds to change their trajectory when approaching blades or to pause blade rotation. Augmented turbines operating efficiently at low rotational speeds and with advanced computation fluid dynamics simulations can cut down noise pollution.

CHALLENGES AND BARRIERS

Although onshore terrain mapping and wind conditions are captured digitally almost everywhere in the world, offshore wind and weather conditions, as well as seabed visualisation and analysis are still not advanced. Surveying the seabed means applying advanced image processing techniques, which is often not economically viable and time-consuming.

Visual impact and noise pollution are the biggest hurdles in the planning and development stage, but blade and tower vibrations also have a major impact on the surrounding environment. To detect and analyse structural vibrations, advanced sensing technology and engineering knowledge are needed to translate the exported data. On a material level, replacing carbon parts with blade carbon fibers involves a long period of testing and simulations to secure safe and extensive use of durable recyclable materials.

FIGURE 9

Bird detection with radar, camera and image processing technology

Source: DHI

CASE STUDIES

The following case study presents an automation solution for maximising wind energy generation while fully complying with local acoustic restrictions at a wind farm in Spain.

Automation of noise curtailments in Gueltas wind farm

OPERATOR:
EDPR

SOLUTION PROVIDER:
Green Eagle Solutions

OBJECTIVE:
Maximise operational strategies while complying with acoustic restrictions.

EDPR has implemented a system that automatically shuts off wind turbines in line with noise restrictions that depend on wind speeds in certain time slots (from 22:00 to 07:00 CET) and during certain wind directions (between 220º and 285º). By using this system, EDPR ensures compliance with restrictions and cuts down energy and revenue loss.

END OF LIFE TREATMENT

TECHNOLOGIES AND BENEFITS

As wind farms approach the end of their expected lifetime, several options are available for the owner on whether continue the farm's operation and how to do it. Modernizing parts of the equipment, repowering, re-blading the wind turbines, hybridising the wind farm with another generation technology i.e., solar PV.

To determine the best option, we can use digital tools to look at inspection and maintenance records and assess the cost and revenue potential of the different alternatives supporting the decision-making process. Hybrid models, which combine material science with data science and site measurements under a damage progression framework can be used to estimate the remaining life of critical drive train components.

Digital twin models can be used to model blade material including aeroelastic simulations and load response. Fatigue damage progression is possible using image processing techniques and finite element analysis software allows for lifetime extension of existing or potential farms. The impact of environmental conditions on blades and substructures – such as erosion and corrosion – is detected at an early stage by remote inspection, preventing further damage. Finally, advanced recycling technologies also allow us to separate materials and recycle blades more efficiently.

CHALLENGES AND BARRIERS

To properly assess energy yields and revenue streams with life extension in mind, digital decision-making tools – usually AI-based - need to be validated by experts both with finance and wind farm engineering expertise. Moreover, to carry out reliable assessments they will need continuous feed-in with material properties and performance data which are not always readily available. As a result, their accuracy is relatively low for the time being. Encouraging data sharing between different wind farm operators will be key to approaching wind turbine end-of-life more cost-effectively[16,17].

CASE STUDIES

Below we present a case study of a digital tool for assessing the lifetime extension of a wind farm considering site-specific conditions. The tool has been deployed at different wind farms at global level.

16. Press Release: Wind systems mag, Digitalisation strategies to extend turbine life, December 2019
17. N. Andersen , O. Eriksson , K. Hillman, M. Wallhagen, Wind Turbines' End-of-Life, Quantification and Characterisation of Future Waste Materials on a National Level, November 2016

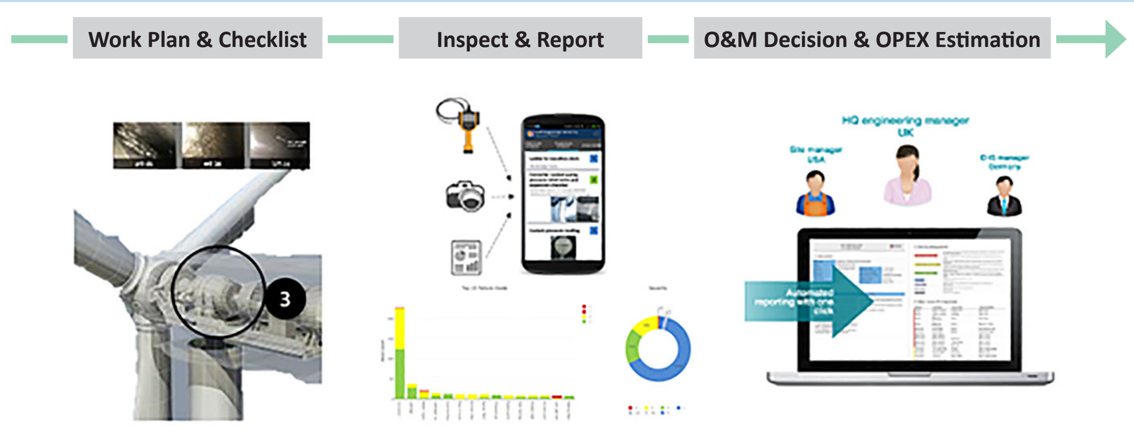
Lifetime extension assessment of a wind farm

OPERATOR:
Not public information

SOLUTION PROVIDER:
ONYX InSight

OBJECTIVE:
Improving the efficiency and accuracy of lifetime extension assessments with a cloud-based inspection platform

Reliability forecasting and assessments are needed to determine the remaining useful life (RUL) and wind farm safety levels during lifetime extension. Typically, the analytical method to quantify RUL and site-specific condition inspections provides critical input to assess safety requirements and the integrity of critical components and systems. Analytical methods such as the aeroelastic model are well recognised by industry. On the other hand, no mature wind-specific inspection solution is available on the market. To bridge the gap, this project delivered a cloud-based inspection tool that streamlines the practical assessment process by digitising inspection checklists and forms while the failure mode database based on the International Organisation for Standardisation (ISO)/ American Gear Manufacturers Association (AGMA) standard is embedded. The platform gives a detailed health status of the wind farm at turbine and fleet level. The statistics consist of an issue punch list, failure modes and a component severity-level heat map. The tool features an End-of-Life (EoL) inspection checklist specific to wind turbine models and images as well as failure modes. Engineer's comments are automatically mapped with turbine components for post processing. This digital tool has reduced inspection time and improved the efficiency of field data reporting. The outputs give insight into guiding potential mitigating actions and recommendations for ongoing O&M decisions and OPEX estimates. Additionally, borescope, drone and thermal image cameras can be integrated.



1.2 ADVANCED OPTIMISATION

WIND TURBINE PERFORMANCE OPTIMISATION

TECHNOLOGIES AND BENEFITS

The optimal performance of a single wind turbine is one of the biggest challenges for the wind researchers and industry communities. And while there has been good progress at the aerodynamic level, the use of reliable data-driven approaches remains a challenge. Supervising performance through SCADA systems and cutting-edge sensors can offer valuable information on critical operations and the condition of the turbine.

Data-based analyses of the exported information can provide a smart failure prediction of different parts. Advanced sensors for analysing vibrations can also pinpoint abnormal operation periods and can help extend the lifetime of blades and subassembly structures.

The term augmented wind turbine describes a new type of turbine capable of operating at lower wind speeds by increasing the wind speed upstream of the turbine. Software platforms and advanced testing sensing devices can also track any improvement in the performance of this innovative technology.

CHALLENGES AND BARRIERS

A reliable digital wind turbine model might ensure full visibility in driving down lost production. However, there are several hurdles to this. The wide variety of turbine models make it difficult to develop a common platform that addresses every performance parameter.

Advanced sensing techniques can identify blade vibrations and cracking growth. However, the response of composite materials to dynamic loading still has not been investigated when it comes to developing predictive damage tools.

Finally, closing the gap between digital research findings and the end-to-life process of turbines is a very long-term process. uncertainties can only be investigated during the operational life of the turbine. In this context, more widespread and standardised data sharing between wind farm operators could do much to make digital models more reliable.

CASE STUDIES

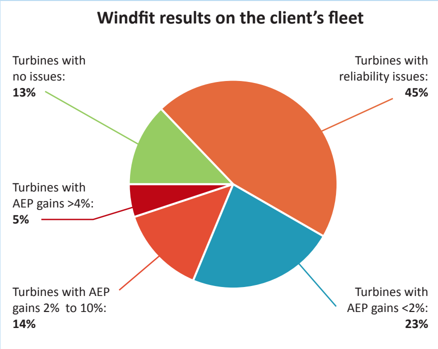
The following two case studies present digital applications in wind turbine performance optimisation: (1) a digital platform used to optimise the performance of 67 wind turbines in Europe (2) an AI platform used for deploying predictive maintenance in a global fleet of wind turbines.

Fleet performance optimisation

OPERATOR:
ERG

SOLUTION PROVIDER:
Sereema

OBJECTIVE:
Enhancing the optimisation of wind turbine performance and preserving its lifetime



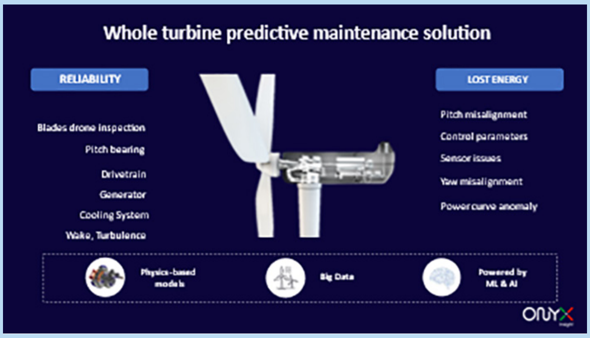
A dedicated monitoring strategy has been implemented for a part of the ERG fleet using Windfit Cloud computing and IoT technology. Wind turbines are equipped with their own "connected watch", a sensing device composed of embedded sensors such as accelerometers, ultrasonic anemometers and magnetic compasses. High-frequency data is continuously gathered independently of SCADA and brought through the cellular network to cloud servers. This data is then processed through dedicated proprietary algorithms to obtain multiple diagnostics on the performance and reliability of subsystems like rotor imbalance, tower vibrations or yaw misalignment. The current project covers a total of 67 wind turbines with the aim of identifying potential issues, taking the right corrective measures and confirming expected improvements in terms of performance, maintenance and the lifetime scope of the turbines.

Artificial intelligence platform for a global wind turbine fleet

OPERATOR:
Not public information

SOLUTION PROVIDER:
ONYX InSight

OBJECTIVE:
Deploying wind turbine predictive maintenance solutions for scalable and efficient fleet management



The AI Hub platform has been deployed globally across a combined fleet of more than 7 GW with more than 20 different turbine models. It helps engineers to go from monitoring hundreds of wind turbines to a few thousand and the lessons learnt on one site can be immediately applied to other sites with the same make/model of turbines. AI HUB can also benchmark a site's performance against similar sites around the world and identify shifts in performance. It can also give recommendations in emergency situations based on previous instances. The tool integrates O&M data streams such as SCADA, maintenance reports, inspection images and vibration analysis. It also reduces the number of software platforms and screens needed for O&M and provides holistic advanced analytics. Meanwhile, the AI approach makes use of an expert team of data scientists and wind engineers to review data, train models and evaluate model performance to maximise sensitivity and minimise false positives. The centralised cloud-based solution gives all teams a single platform to share analytic reports, inspection/maintenance reports, photos and comments. Current deployment has led to significant savings, including a reduction of LCOE costs by up to 12%, a 2% increase in availability and a 30% increase in lower maintenance costs.

WIND FARM DESIGN OPTIMISATION

TECHNOLOGIES AND BENEFITS

The term of the digital wind farm describes a digital model of physical aspects helping to improve wind farm power output. This includes a range of customised hardware and software tools. New wind farm digital software applications help to optimise business and operations and strengthen asset performance management – namely in terms of enterprise SCADA, diagnostics and energy output prognostics.

Digital visualisation and wind farm monitoring help to address losses based on wake effect, wind shear and layout optimisation. Software platforms and tools strengthen advanced probability models for wind and waves, including extended weather forecasting, which translates into efficient logistical planning and load conditions. This leads to smart monitoring of loads damage to construction and probabilistic planning and costing of logistics.

These solutions also reduce downtime periods and extend the predicted lifetime of components., Digital tools can also predict wake losses and map out different layout scenarios for optimisation, strengthening Balance of Plants (BoPs) in terms of the supply, installation and Engineering, procurement and construction (EPC) phases.

CHALLENGES AND BARRIERS

Terrain, spacing and local wind conditions require unique solutions when it comes to each farm's layout. Engineers look for innovative solutions for offshore wind farms and still investigate the impact of regular and irregular wave and wind loading on foundations and turbine substructures. Existing knowledge of offshore structures, inherited mostly from the oil and gas industry, can help speed up optimisation processes.

But the wind industry has to simplify existing software platforms, make them lighter and reduce their operational costs. The stochastic nature of weather parameters, wake effects and turbulence add to the uncertainties of generated data models and keep developed data-oriented solutions from being more widely applied.

An extra hurdle to developing optimal wind farm designs is the balance between power performance and lifetime extension. This requires extensive, continuous monitoring of different entities on the farm and tracking new material properties, design configurations and grid connection solutions.

CASE STUDIES

The following case study presents a digital application to optimise the design of a wind farm in a complex terrain considering different wind turbine layout scenarios and the subsequent wake effects.

Wind farm simulation and layout optimisation in complex terrain

OPERATOR:
Not public information

SOLUTION PROVIDER:
National Renewable Energy Laboratory (NREL)

OBJECTIVE:
Layout optimisation simulation of an as-built wind farm in complex terrain and validation by comparison against SCADA data from a real wind farm

This project demonstrates layout optimisation in complex terrain using an opensource computational fluid dynamics (CFD) tool from the National Renewable Energy Laboratory (NREL) called WindSE[18]. This aims to simulate the wind flow within a given domain and turbine layout. The system of equations is constructed in Python using FEniCS tool as its finite element backend and grants control of inputs such as turbine location, yaw and axial induction, modifications to the computational mesh and inflow boundary conditions. Simulating the modification of different parameters has shown major changes in the trajectory of wind turbine wake effect not properly captured by traditional engineering flow models. Different layout scenarios led to a 123.2% yield improvement in the objective function compared to the starting configuration with a gridded layout.

18. J.Allen, R.King, G.Barrett, Wind farm simulation and layout optimisation in complex terrain, 2019

O&M OPTIMISATION

TECHNOLOGIES AND BENEFITS

Integrating multiple data sources allows information about inspection, environmental and operational data to be analysed and combined onto centralised software platforms. These platforms enhance business and operations optimisation and lead to better O&M management, in terms of enterprise SCADA, diagnostics and energy output prognostics. Digital visualisation and monitoring of wind farms can help to adjust losses, develop model-based reasoning and apply failure diagnosis.

These solutions also prevent fatigue damage, shorten downtime periods and extend the expected lifetime of critical components. An efficient root cause analysis leads to scheduled predictive maintenance which enables accurate logistics assessment and the development of long-term O&M strategies.

These decisions help companies to make smart business decisions by setting the right KPIs to increase revenue. This risk management approach can reduce financial uncertainty and lead to a systematic realisation of asset values.

CHALLENGES AND BARRIERS

Unique terrain and weather, different turbine models, materials and capacity need specific maintenance solutions for each wind farm. There is limited integration between different platforms and many farms are lacking basic sensing infrastructure. Existing knowledge of offshore structures, especially from the oil and gas sector, can accelerate optimisation processes, but the sharing of knowledge strategy is not widely adopted between industries.

The wind industry needs to continue simplifying, make existing software platforms lighter and reduce operational costs. Preventive and predictive maintenance models need to reduce the risk of error and offer widely applied data-models. Again, in this context, the deployment of a universal data standard would be a major enabler.

CASE STUDIES

Below we present two case studies of digital applications in wind farm O&M optimisation: (1) an asset dashboard tool optimising O&M in an international fleet of wind and solar assets and (2) an analytics tool identifying early-stage failures of gearboxes in a wind farm with 100 wind turbines.

Asset dashboard tool

OPERATOR:
Iberdrola Renewables

SOLUTION PROVIDER:
Everis

OBJECTIVE:
Optimising O&M processes with optimised parameter visualisation

This tool shows key operational KPIs from Iberdrola's wind and solar PV assets – real-time production, 5-day power forecasting and deviation from the annual budget, electrical parameters, capacity factors, component failure diagnostics, lack of energy availability and the causes of this and maintenance information including open work orders, preventive and pending tasks. Information is categorised on a daily, monthly and yearly basis. It also monitors weather alarms, provides weekly weather forecasts and registers lightning strikes.

Fast return to operation

OPERATOR:
Various

SOLUTION PROVIDER:
ZF Wind Power

OBJECTIVE:
Using alert-based analytics to identify early-stage failures and improve planning and service execution of wind turbine gearboxes to maximise the annual energy production (AEP)

Based on the digital birth certificate and service intervention data, ZF can tell what failure modes are most likely to occur per gearbox model, as well as the associated risk level. Cloud-integrated input from a condition monitoring system (CMS) supplier feeds the alert-based analytics and points out which failures are most likely to occur – and thus enables prescriptive maintenance. Results from a one-year case study with SKF on a site with 100 turbines have shown a 50% reduction in alert processing effort, a 60% decrease in field inspections, an 85% decrease in lead time to repair and a 0.4% AEP increase at wind farm level.

WIND FARM REVENUE OPTIMISATION

TECHNOLOGIES AND BENEFITS

Accurately estimating and optimising a wind farm's power output is a multifactorial task. Furthermore, integrating a wind farm's exported power with the energy market increases complexity and uncertainty. However, understanding how the wind farm participates in the energy market, combined with the proper exploitation of reliable cloud-based performance data, can bring about a significant increase in revenue.

Hybrid software platforms which assess forecasted weather, turbine settings and grid status can help cut energy losses and ensure an ideal market bidding strategy. Optimisation algorithms based on revenue instead of power yield can also take life-time extension parameters into account.

CHALLENGES AND BARRIERS

In this case, the diversity and unpredictability of these parameters limit data-based models' accuracy. As a result, customised models for specific conditions cannot be used to optimise revenue across a wide range of energy markets and wind farms. To improve distribution models and achieve ideal revenue algorithms, access to reliable and well-structured data is also crucial in this case.

Efficient data sharing policies can support this effort. Additionally, if we want to develop reliable tools, we will need human resources with diverse skillsets: advanced IT skills, wind energy engineering backgrounds and a knowledge of energy markets.

CASE STUDIES

The following two case studies present digital applications in wind farm revenue optimisation: (1) an analytics tool used to maximise wind farm AEP based on SCADA data and (2) an AEP optimisation tool based on advanced wind turbine and wind farm level yaw control.

Improved wind farm revenue optimisation

OPERATOR:
No public information

SOLUTION PROVIDER:
WindESCo

OBJECTIVE:
Increasing wind farm revenues during repowering using Swarm, a farm-focused, closed-loop wind farm revenue optimisation system

The WindESCo Swarm is an autonomous, closed-loop, AEP farm-level optimisation system. The system is designed to overcome key barriers to wind farm optimisation such as autonomous wind turbine operation which prevents data sharing between turbines and promotes 'greedy' turbine operation. Analysis shows that wake steering, deployed by most AEP optimisation tools, is often not enough to achieve a boost of AEP at every site. The WindESCo Swarm is a system of applications that strengthens the precision and accuracy of both turbine and wind farm-level yaw control using closed-loop (i.e. strategies not based on a static look-up table), wake mitigation, yaw control aid and online static yaw misalignment correction. This system does not require any change to wind turbine controller logic.

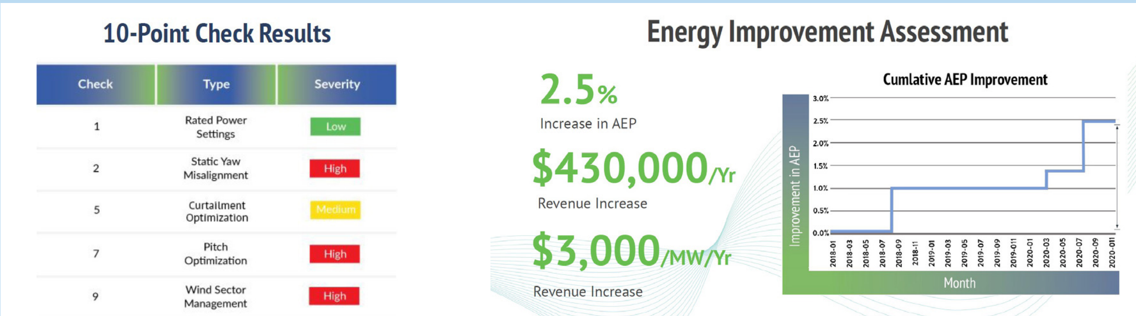
Find-Fix-Measure

OPERATOR:
Longroad Energy

SOLUTION PROVIDER:
WindESCo

OBJECTIVE:
Increasing wind farm AEP by leveraging SCADA data to optimise energy output

The project aims to increase revenue by addressing hidden revenue losses at a wind farm level. The Find-Fix-Measure helped Longroad Energy secure $430,000 in annual revenue from a 145 MW acquired wind farm, increasing energy production by 2.5%. The technology uses advanced analytics, proprietary algorithms and domain expertise. Using a combination of engineering, ML and experience models applied to SCADA data, the tool increases turbine output by detecting specific turbine underperformance. It then comes back with recommendations and specific actions to fix inefficiencies and thus strengthening the wind farm's maximum output. Out of 10 data checks, five needed further investigation to identify more opportunities for optimisation. With a better understanding of these factors, the fixes with the greatest potential impact on the project were implemented. Yaw misalignment and pitch settings are both remedied using AI algorithms, boosting annual plant revenue by $3,000/MW.



2. DIGITALISATION IN WIND TURBINE MANUFACTURING & CONSTRUCTION

The costs of wind energy will continue to fall over the next 30 years mostly thanks to turbine innovations. These will lead to lower Capital Expenditure (CAPEX), higher capacity factors and longer lifetimes[19]. For offshore especially, the main drivers of cost reduction will be related to CAPEX – upscaling of turbine sizes, material efficiencies due to performance improvements and leaner designs and better installation techniques and processes. For floating technologies, the big drivers will be leaner floater and mooring designs, optimised manufacturing and assembly and moving from "one-off" production series to serial production.

Under this system, advanced manufacturing of wind turbines will become more important. Operational and information technologies will be combined to boost factory output and cut costs. Automation, robotics, advanced sensing and AI should enable breakthrough innovation in products and manufacturing processes, supporting shorter development cycles and more modular manufacturing.

The digitalisation of wind turbine manufacturing and construction is still in its early stages and remains a difficult task. Great precision is needed to handle structures with complex geometry. Validation cycles for testing the efficiency of different designs are long because real operational data need to be assessed. As in the case of wind O&M, a range of technical skills are needed to ensure reliable digital tools in the manufacturing process. This means a greater need for a more diverse workforce and additional training courses.

Wind turbine construction, particularly offshore, requires many different actors and their individual systems. All these factors add to the need for automated processes that would scale up production. But the transition from manual to more digital manufacturing will be quite resource demanding.

Given the contribution of advanced wind turbine manufacturing and construction techniques in driving down costs and improving technologies, the following paragraphs look at some digital applications in these areas. It is important to note however that this is not an exhaustive list of what is currently applied.

19. ETIP Wind, WindEurope, "Getting fit for 55 and set for 2050", June 2021

WIND TURBINE DESIGN AND MANUFACTURING

TECHNOLOGIES AND BENEFITS

A functioning wind turbine consists of several major and secondary components. The complex design and the cost of building wind turbines requires the implementation of digital tools and software solutions that can automate and standardise operations. Figure 10 shows an automation technology for wind turbine blade testing. From conception to production, digital technologies such as generative and parametric design, 3D scanning, virtual reality, augmented reality, IoT, sensor technology, big data and computation power have made great progress in the last few years. These new technologies can fundamentally change the design process and offer major benefits across the supply chain.

The digital approach to manufacturing processes not only shortens the time needed to develop new product designs but leads to falling ownership costs, as future design platforms will explore the solution space more thoroughly than humans can do at present. Digital twin models of critical components and structures can support design optimisation and better performance via numerical software simulations. This makes the design process more flexible and allows for more customised product designs.

The digital design and production approach also encourages full supply chain optimisation, with data driven management strategies for the whole cycle of production. Ultrasonic laser technology can be used for testing and production control of wind turbine blades. This allows bonding imperfections at the material level to be detected and inspected more accurately, through sensors. Along with composite equipment inspection, lightweight robots can cut manufacturing time and carry out an efficient and detailed assembly.

FIGURE 10
Automated testing for wind turbine blades

Source: ORE Catapult

CHALLENGES AND BARRIERS

Given the range of wind turbine components and materials, customised and unique digital modelling is needed for each one. This makes the task of developing a single digital wind turbine model very challenging. In the case of interactions between substructures and advanced control methods, long testing and validation processes are needed to make reliable observations.

Optimal design, manufacturing and performance monitoring mean that human resources with diverse skills (mechanical engineering, software development, material engineering) also need to work together as part of the same project. Other major drawbacks include the cost of automated manufacturing solutions and a lack of IT resources. To automate wind turbine production, high precision and speed are needed to produce geometrically complex components i.e., blades and gearboxes.

CASE STUDIES

Below we present three case studies of digital applications in wind turbine manufacturing: (1) a 3D printing solution for the casting components of an offshore wind turbine, (2) a digital platform supporting the design of blades based on cost-effectiveness and performance criteria and (3) a monitoring solution for blade casting.

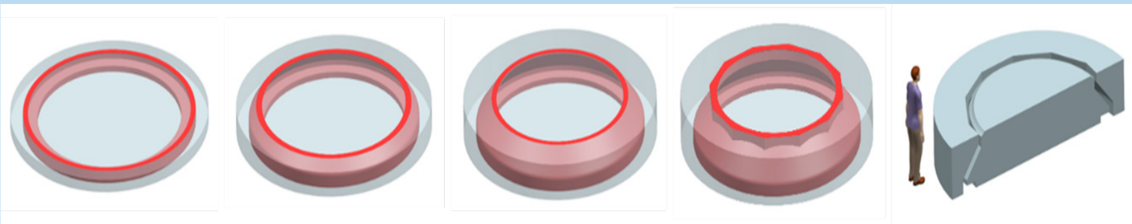
3D printing solution for offshore wind turbine components

MANUFACTURER:
GE Renewable Energy

SOLUTION PROVIDER:
Fraunhofer IGCV/ Voxeljet AG

OBJECTIVE:
Optimising the production of casting components

This tool aims to improve the production of casting components for GE's Haliade-X offshore turbine with the Advance Casting Cell (ACC) 3D printer[20]. The ACC is capable of printing molds for key components of the turbine nacelle. A research partnership to develop the world's largest 3D printer for offshore wind applications – which if completed will be able to print molds casting the components of a turbine nacelle up to 9.5 metres in diameter and weighing over 60 tonnes in weight. This large 3D printer format could produce sand molds for casting complex metal segments making up offshore wind turbine nacelles. This milestone in manufacturing technology will significantly cut transportation costs and reduce carbon footprint of casting components' production.



20. Press release: GE, GE Renewable Energy, Fraunhofer IGCV, and voxeljet AG plan to develop world's largest sand binder jetting 3D printer for offshore wind turbines, September 2021

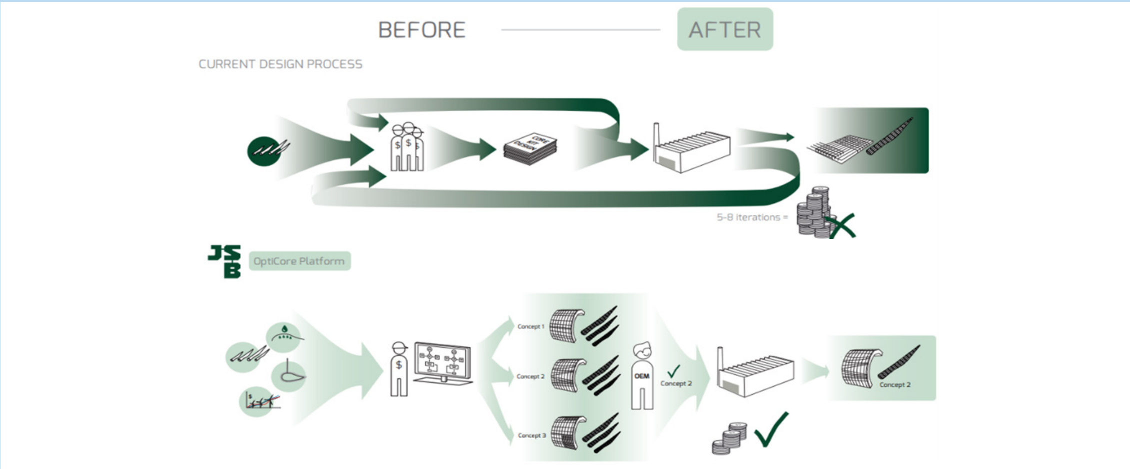
OptiCore platform

MANUFACTURER:
Gurit

SOLUTION PROVIDER:
Gurit & DTU

OBJECTIVE:
Creating a new design platform allowing Gurit to explore the entire solution space defined by customer design parameters and constraints and to improve product design

The OptiCore platform aims to digitise the design process to maximise the cost-effectiveness and performance of core kit designs. It is based on a set of optimisation algorithms that help to improve blade core kit design–accounting for parameters like blade geometry, resin uptake, weight, resin flow, infused mechanical properties, manufacturing costs and Health and Safety requirements based on blade OEMs or end-user needs and constraints. The next step is to integrate the OptiCore platform directly into the blade manufacturers' full 3D blade models. This would mean significantly shorter development lead times, high consistency, quality in technical documentation and would maximise design process automation.



Blade casting monitoring

MANUFACTURER:
Siemens Gamesa Renewable Energy

SOLUTION PROVIDER:
IBM

OBJECTIVE:
Using ML technology to improve the speed and efficiency of wind turbines manufacturing

This tool has addressed the need for cost reduction with data-driven manufacturing solutions for wind turbine blades[21]. An ML spell out solution has been created on Microsoft Azure, using a laser grid to show precisely where each fibreglass layer should be placed. It applies multiple technologies, including computer vision, ML, edge computing and Internet of Things (IoT). Thanks to IoT-connected cameras in factories and continuous analysis using ML models at the edge – all managed-on Microsoft Azure – the technicians can assign each blade layer with greater speed and accuracy. The solution gives human operators greater insight during the manufacturing process. With that knowledge, they can intervene early on when temperatures or pressure are outside the ideal range. With this, operators can intervene to recalibrate the temperature and avoid defects that would otherwise call for extensive repairs. They can also evaluate historic data to improve new designs.

21. Press release: Siemens Gamesa, Siemens Gamesa learns how a classic manufacturer becomes a digital player, with guidance from Microsoft, January 2021

WIND TURBINE CONSTRUCTION AND LOGISTICS

TECHNOLOGIES AND BENEFITS

To build a wind farm safely and successfully, several tasks need to be addressed in a timely manner often under challenging weather conditions. Heavy and sensitive equipment needs to be carried and placed onshore or offshore. Unmanned aerial vehicles (UAVs) carrying surveying equipment and intelligent cameras can provide data on the topographic layout of the area. Figure 11 shows a dynamic position system for autonomous service operation vessels.

Along with professional data glasses and gloves, IoT and radio frequency identification technologies can provide real time monitoring of the construction process and the condition of the delivered equipment. For instance, cabling and sensors status and functionality can be checked even before they are fully operational.

Automated vehicles can move substructures onshore and within port areas while standalone cranes and vessels can carry heavy loads with high accuracy and safety offshore. Thus, by applying digital manufacturing and transportation techniques, a centralised task software platform can be developed that improves efficiency and reduces the project's operational costs.

CHALLENGES AND BARRIERS

The digital transformation of wind farm construction is not yet fully mature mainly due to the costs of autonomous equipment and connectivity infrastructure. At the same time, the use of advanced manufacturing and transportation tools involves giving staff the right training and may also require the development of remote-control rooms. It also involves developing an efficient Building Information Modelling (BIM) that should integrate existing construction standards, such as Eurocodes and data standards and legal frameworks for any technology applied on site. This is needed to track collaboration between the different stakeholders (developer, technology supplier, contractors…) and to outline rights and responsibilities in case of accidents or system failure[21].

FIGURE 11
A dynamic position system for autonomous service operation vessels[22]

Source: offshoreWIND

CASE STUDIES

The following case study presents the application of autonomous vessels for offshore wind farm inspections.

Autonomous vessel for offshore wind farm

PROJECT DEVELOPER:
ORE Catapult

SOLUTION PROVIDER:
L3 Harris/Houlder/SeaPlanner Ltd/University of Portsmouth

OBJECTIVE:
Introducing autonomous vessels in wind farms to reduce the number of offshore onsite inspections and respective O&M costs

A £900k joint industry project is set to explore the technical, regulatory and societal barriers to deploying autonomous surface vessels, integrated with existing manned shipping operations, to support offshore wind farm operations and maintenance. Across all O&M expenses, vessels and staff make up 60 – 65% of costs. Significant cost reductions are possible through the introduction of robotics and AI. Greater use of autonomous vessels will also lead to more highly skilled, cross-sector jobs in areas such as the integration and planning of autonomous vessels, which would boost maritime and digital supply chains. Different stakeholders for this project assist in monitoring and operating autonomous vehicles and introducing advanced cargo planning systems, support route planning, logistics management and system analytics. They also help to develop the vessel design and provide an innovative handling system to allow for autonomous cargo transfer.

22. Press release: offshoreWIND, IHC Tests Autonomous Service Operation Vessel's DP System, June 2020

3. ENABLING TECHNOLOGIES FOR WIND ENERGY DIGITALISATION

This chapter presents the use of generic technologies enabling many of the previous digital applications in wind farm O&M and wind turbine manufacturing and construction.

CONNECTIVITY

TECHNOLOGIES AND BENEFITS

The introduction of innovative wireless technologies is a major step forward for the wind industry. Offshore installations are being developed further away from shore. They now require advanced communication solutions between staff in the control rooms, onsite technicians and the different monitoring systems.

The transition to private 5G industrial network technology has an immediate impact on the connectivity of wind farms. The replacement of 3G services and very high frequency (VHF) radio communications with private LTE/4.9G and 5G wireless network solutions enable broadband connectivity and next generation voice and video capabilities in the field.

Augmented reality (AR) artificial environment and virtual reality (VR) computer generated simulations offer a realistic virtual experience of physical elements and conditions[23]. The Industrial Internet of Things (IIoT) allows for direct connectivity among sensors. Wireless network sensors (WSNs) and ML technologies allow advanced remote monitoring beyond SCADA. Remote land-based operations are a major boost to safety and productivity and offer real-time alert and communication in the case of emergencies. The risk of accidents is minimised during blade inspection, as increased connectivity enables image processing techniques with drone inspections and scene cameras for fatigue damage detection.

23. GE, Augmented reality | GE News, August 2019

CHALLENGES AND BARRIERS

The use of modern connectivity solutions involves updating existing communication systems and access to lower or higher wireless frequency bands to deliver 5G coverage. There is also the cost factor of new infrastructure and advanced hardware equipment, as satellites and advanced sensing devices are considerable expenses. Another concern is the compatibility of monitoring software platforms with recently developed technology and sensors.

Many onshore wind farms seem to be unprepared for upgraded communication, as the existing facilities do not support advanced solutions. Enabling offshore wind farm connectivity might even call for the use of micro-satellites if they are located far from shore. Finally, a massive increase in transferred visual and auditory data from vast equipment connection, visibility and control must be factored in. Offsetting this will require outfitting proper control rooms and cloud services to be used as storage.

CASE STUDIES

Below we present a case study of the application of a private 4G and 5G network in two offshore wind farms in the UK.

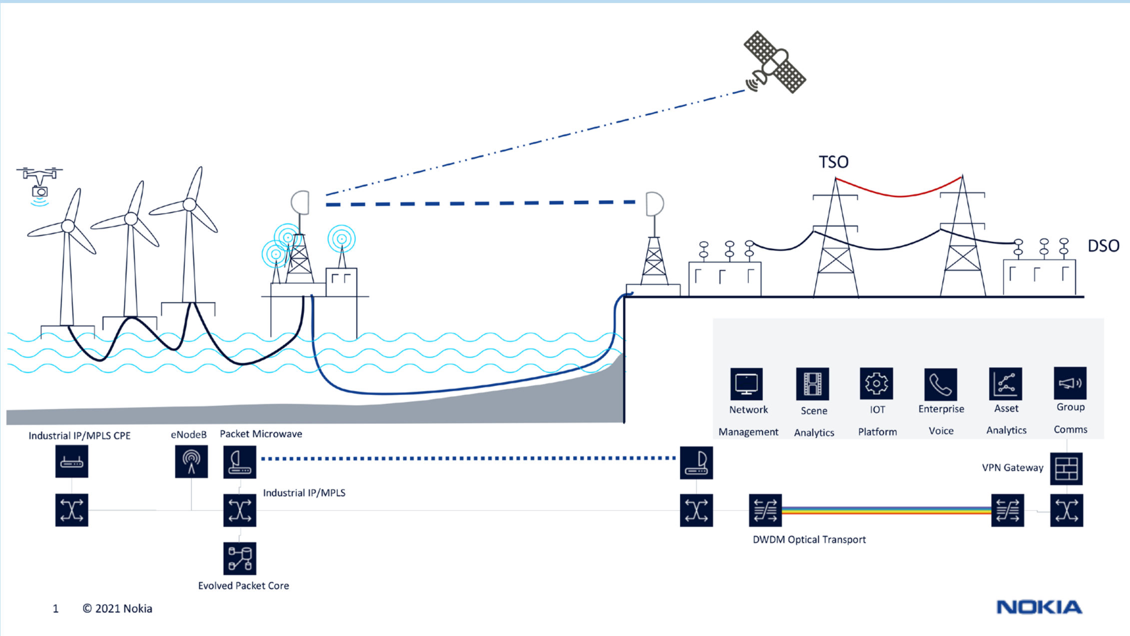
Private 4G-5G in Dudgeon and Sheringham wind farms

PROJECT OPERATOR:
Equinor

SOLUTION PROVIDER:
Nokia/NetNordic

OBJECTIVE:
Private 4G-5G network solution for Dudgeon and Sheringham wind farms

This 8-year project involves hardware, software and design support, as well as radio planning and implementation guidance for the delivery of offshore digital wireless tools (Nokia DAC solution, 4.9G LTE and 5G Radio Access Network technology, Nokia Industrial devices). The project aims to enforce communication and maintenance tasks and increase staff safety. It will also provide a range of access points both for coverage of the Service Operation Vessels (SOVs) and an edge solution with complete packet core and application framework for edge computing.



BIG DATA

TECHNOLOGIES AND BENEFITS

The ongoing expansion of wind energy, supported by advanced sensing and wireless connectivity solutions, has led to a major growth in data volume and data collection sources. The need for data storage, manipulation and analytics has grown considerably. Web-based cloud services and upgraded SCADA systems are being developed to ensure standard labeling and categorisation in exploiting databases and improving traceability and data quality.

As SCADA systems allow signals on a specific frequency range, advanced cloud services are needed to monitor system and components operation, allowing failure estimation. The IoT cloud analytics collect data from back-office systems, allow individual access control for multiple partners and model execution to deliver results and KPIs to the O&M end-user layer.

Furthermore, data pools including information on reliability parameters, maintenance strategies, life cycle costs and performance monitoring helps to cut down on paperwork and offers management support by modelling operating data and optimising customer customised analyses, as component suppliers. Furthermore, confidential indoor trends and insights are analysed and displayed in a way which can be shared with third parties for further deployment.

CHALLENGES AND BARRIERS

The development of data pool structures often involves assembling data from different systems operated by different stakeholders. Alongside the need for shared standards for interoperability and for comprehensive data security strategies, there is also a need for openness to third-party data sharing concepts.

Another major area of concern is data reliability. Lack of reliable data and conflicting views on data quality between different stakeholders both add to the uncertainty of exploited results. Different types of data groups – equipment, operating and failure – are used for developing various analyses. As the accuracy of these statistical analyses, vibration and fluid modeling and maintenance optimisation is based on the inserted data, deploying well-structured databases is key. There is also a need for continuous staff training to be able to identify data quality.

The clearest way to make the most out of data is to encourage an open-door policy on data access and to improve the quality of analyses to reduce the risk of human error. Importantly manual paper records are still used in some parts of the sector, which disrupts digitalisation efforts. Historical data from more than 20 years ago was never designed to be used in modern analytics and requires digitisation.

CASE STUDIES

Below we present two case studies of big data applications: (1) an O&M management platform for aa Belgian wind farm with 44 wind turbines supported by big data storage and (2) a high-performance big data storage system for weather forecasting data used in wind farm operation.

O&M management platform with big data storage in Norther wind farm

PROJECT DEVELOPER:
Elicio NV/ Eneco Wind Belgium SA

SOLUTION PROVIDER:
e-BO Enterprises

OBJECTIVE:
Deployment of an integrated offshore wind management platform aiming a maximum efficiency through data capturing

Norther is an offshore wind farm in Belgium with a total of 44 wind turbines and a maximum capacity of 370 MW. The project includes the delivery of a complete O&M platform, supporting Big Data storage for data collection/ management. The O&M platform allows Norther to not only monitor their asset performance but also to follow-up on the maintenance planning and coordination of offshore works including permits to work and transfers as well as handling staff safety (QHSSE, safety inductions, ...) and stock. The system is also connected to ICCP, CMS (structural information), DTS (cable monitoring), weather forecasts, WTG & OHVS SCADA and employer database as well as with live meteo and tracking (vessel/person) data from within the field. To benefit from available wind farm data, the platform provides the necessary APIs to third-party actors (like off-takers, DTS, CMS as well as research programmes). Norther is compatible to the BI environment (Tableau) and is using Python and other programming tools to extract and transform the data further for research purposes. With this approach the developer maximises the use of data to create better insights, increase efficiency by having direct live access to all the information and to build up a future database for projects/challenges in the future.

Big data storage system of high performance

PROJECT DEVELOPER:
Météo-France

SOLUTION PROVIDER:
ATOS

OBJECTIVE:
To increase data storage capacity to over 1 exabyte for improving numerical modelling and climate predictions

The solution aims to supply a new mass storage system to store and manage the vast volumes of data which are mainly produced by Meteo France weather forecasting models and by its research work on climate change. Annual extensions over a five-year period will enable the storage capacity to reach 1.3 exabytes (1,300 petabytes) by 2025, enabling it to ingest and render up to 2 and 1.3 petabytes of data per day, respectively. The new storage system is based on the high-performance storage system (HPSS) solution for which Atos has developed a complete environment which monitors and administrates storage performance and provides support and maintenance throughout the whole lifecycle. This architecture combines disk and tape storage technologies, guaranteeing efficient access times for the most frequently used data, while keeping less frequently accessed data accessible (nearline) in tape robotics.

4.
THE ROLE OF DATA

In most digital applications we have stressed the importance of data reliability and efficient data manipulation as a major enabler and challenge. Recently the European Commission published its action plan for the digitalisation of the energy sector[24]. Its first focus area is the development of European data sharing infrastructure to promote demand-side flexibility and to support planning and the monitoring of energy assets. This infrastructure could also feature a common EU energy data space, compatible with other data spaces, based on a commonly developed interoperability framework.

Today there is clear need for an interoperability framework among the energy sectors and within the electricity sector itself[25]. This also applies to the wind sector, which lacks a commonly accepted wind data standard. Covering this gap would be a major steppingstone in enabling data sharing practices and collaboration among different actors (turbines manufacturers, wind farm operators, third parties), leading to greater cost reduction and innovation.

24. European Commission, Action plan on the digitalisation of the energy sector, July 2021
25. WindEurope, Making wind farms and the power system more interoperable: Focus on data exchange, March 2021.

4.1 WIND DATA STANDARDS

Wind farm development and operation has introduced new terminology and has created the need for a new technical vocabulary to allow communication within the wind workforce and with third parties. From wind resource assessment to wind energy delivery, there is a need for universal labelling of mechanical and electrical components and for data standardisation.

Data standardisation is needed to support system integration, performance monitoring and equipment certification and to promote efficient data storage. This is particularly relevant for already digitised processes. But there is also a need to digitise stored historical bulk data – either in paper or excel form – from several operational years. To exchange and analyse this information, a data standard is needed to allow different systems and users to communicate and to make the necessary links between fully and partly digitised processes.

Today a set of standards and regulations offer a baseline for data modelling and classification in wind operation[26]. These are outlined in Figure 12. Some of these standards give useful high-level terminology but do not cover all necessary labelling needs for components, error codes, signals, availability, maintenance optimisation parameters, risk assessment and other parameters. There are a few gaps that still need to be covered.

The two major data standardisation needs now are in the areas of grid integration and in wind farm development and O&M:

- Grid integration: Electricity transmission and grid connection data can be modelled with Common Information Models (CIM) that are aligned with those of Transmission System Operators (TSOs) and the International Electrotechnical Commission (IEC). Several IEC CIM standards exist to support necessary data exchanges to ensure grid stability and efficient system operation[27], but they do not cover the entire portfolio of wind farm parameters. A few parameters including behind-the-meter grid topology, power system variables and load values are not fully defined. There is a need to deploy a commonly agreed data standard that can be widely applied and which could cover both new and legacy wind farm systems for efficient data exchange with grid operators[28].

- Wind farm development and O&M: Another level of data standardisation is needed to tag and certify different wind farm components and applications. Beyond reliability and calibrating the required tools, such as sensors and anemometers, data standards are key to certifying the quality of critical operating components. Specification, evaluation and verification of blades, generators, brakes and several different substructures are covered by IEC, ISO and European Standards (EN)[29]. The introduction of new materials and the wide range of sub-components, the use of new sensing devices and new wireless technologies will lead to a massive increase in data volume, requiring new precise guidelines to ensure safe operation and efficient control. Thresholds for wind turbine performance and the operational status of critical components will also be needed to allow for a common monitoring strategy and maintenance techniques.

26. IEA Wind, "Expert group on recommended practices, Wind farm data collection and reliability assessment for O&M optimisation", 2017
27. ENTSO-E, Common Information Model
28. WindEurope, "Making wind farms and the power system more interoperable: Focus on data exchange", March 2021
29. DNV GL, "Type and component certification of wind turbines according to IEC 61400-22", January 2018

FIGURE 12

Overview of existing standards and guidelines in wind reliability analysis and O&M optimisation[30]

DATA GROUPS/ TAXONOMIES	EQUIPMENT DATA	OPERATIND DATA/MEASURE-MENT VALUES	FAILURE/FAULT DATA	MAINTENANCE & INSPECTION DATA
RDS-PP	●			
GADS	●	▬		▬
ReliaWind	●			
ISO 14224	○		✙	✙
ZEUS		●	✚	✚
IEC 61400-25		✚		
IEC 61400-26		●		

✚ wind specific entries a high level of detail
● wind specific entries a medium level of detail
▬ wind specific entries on a more general level
✙ entries with a high level of detail, not wind specific
○ entries with a medium level of detail, not wind specific

Source: IEA Wind Taks 33

Alongside this need for a universal data standard going into the necessary level of detail, the need for a universal metadata[31] and processed data (generated by the different digital tools) standardisation will also become more acute in the years ahead. Standardising both data groups would, for instance, allow for standardised assessments of the benefits of wind digitalisation technologies. It could also help to draw reliable conclusions on how to improve the design of different technologies based on statistical analysis of operational data and common metrics to assess wind O&M data quality.

Developing a universal data standard could be very challenging and time-consuming. However, the wind sector must come together and make it a reality. It would underpin the transformation of wind energy, reducing LCOE and supporting the transformation of the energy sector overall. Such a framework should cover all aspects of wind farm development and O&M. This includes data related to weather conditions, aerodynamics performance and electromechanical equipment. To interact with energy markets, a system of common labelling would be key to unleashing the potential of previously mentioned digital applications and tools.

30. IEA Wind Task 33, "Wind farm data collection and reliability assessment for O&M optimization", 2017
31. Metadata is data that provides information about other data but not the content of the data. In wind O&M metadata is used for statistical metadata.

4.2 DATA SHARING

Wind energy data storage and management are supported by different digital tools and standards. These tools are vital to take advantage of all the previously described digital applications and technologies. But the wind industry is wary of widely applying data analytics and digital asset management tools to most stages of the wind farm operating cycle. This is mostly due to the lack of established practices and frameworks for data sharing not only with third parties but also within organisations.

The benefits of applying these practices to wind farm development, O&M cost reduction and revenue optimisation still need to be reliably measured. Aviation, oil and gas or the shipping industry could serve as examples of how to go about building such a data sharing mindset. In the oil and gas industry, sharing big data including seismic knowledge, weather conditions and operational historical results has enhanced oil recovery from existing wells, improved the performance accuracy of forecasting models and has enabled the early detection of well issues. Aviation data sharing between operators has helped to improve flight management and build a healthy safety culture in the industry. Data sharing is also one of the focus areas in the Commission's recently proposed action plan on the digitalisation of the energy sector.

A recent spread of data sharing programmes among wind farm owners, operators and national authorities is encouraging and will lead the way for further deployment. Wind farm operators collect and manipulate operational data from their wind farms and make efforts to exploit them in data exchange projects aiming at improving operational performance. The outcomes of these efforts can serve as examples for deploying data sharing elsewhere.

But aspects related to cost, legal frameworks, market regulations, a lack of structured agreement templates in contracting and other factors have all prevented data sharing strategies from scaling up quickly. In the case of data privacy regulations for example, international agreements could be made to allow for exchanges between specific energy sector data groups for statistical purposes. As discussed in 4.1, a universal labelling of wind data is the first step needed to encourage cost-effective data sharing between systems and stakeholders. Collaborative innovation programmes and resources need to be dedicated to develop such a wind data standard and to demonstrate the benefits of data sharing in wind operation. This will be a key milestone in the wider deployment of digital applications mentioned in Chapters 1, 2 and 3.

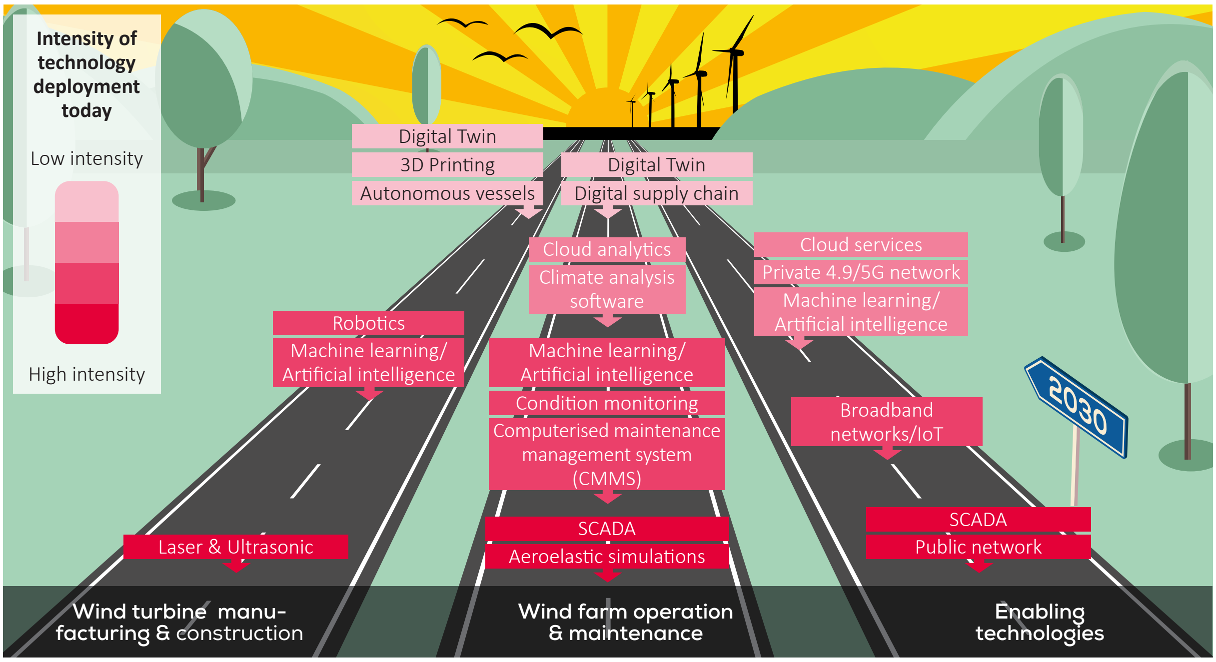
5.

ROADMAP TO WIND ENERGY DIGITALISATION TOWARDS 2030

The first three chapters of this report define major digital applications in wind energy as well as the various technologies that are used to deploy them.

Figure 13 lays out WindEurope roadmap for a digital wind sector by 2030 and the application intensity of digital technologies today.

FIGURE 13
Roadmap towards a digital wind sector by 2030 and the application intensity of digital technologies today



Source: WindEurope

Experience from current deployments across Europe shows a set of recurring barriers that are holding back the digital transformation of wind. To remove these barriers, WindEurope recommends the following strategies and actions:

- **Understand the benefits of digitalisation:** many of the technologies currently used in digital applications need additional infrastructure or new skills to unleash their full potential. This translates into costs added to the cost of the specific technologies. Clear visibility on pay-off times and a proper measure of the benefits are crucial to scaling up the digital applications. But organisations also need an innovative mindset when setting strategies for long-term cost reduction and performance improvements. Developing universal metrics to determine the benefits of different digitalisation projects and investments will be key. Knowledge sharing platforms between interested parties can also support this move.

- **Develop a universal data standard:** developing a universal and comprehensive data standard is the most important enabler of digital applications in wind energy today. This should cover new and old systems, their components and subcomponents and all wind development and O&M steps. It should also consider and complement existing international standards (e.g. IEC61400-25). To accelerate wind system integration, this data standard should also be compatible with respective grid data models[32]. Movement in this direction will depend on the efforts of the electricity sector to develop such a standard and to encourage its wider use.

- **Establish efficient data sharing practices:** data sharing practices are seen as major enabler of wind digitalisation by many organisations, but their benefits have not yet been properly measured. According to its roadmap for the digitalisation of the energy sector, the European Commission will focus on promoting data sharing between actors and sectors and on creating common EU data infrastructure. To remove bottlenecks, RDI resources should be used to measure the benefits of these practices, not just horizontally among energy sectors but also by looking into individual subsectors that are expected to grow exponentially in terms of data volumes (due to technology complexity, expected installed assets' capacity, number of involved actors…).

- **Validate the technologies and make them transferable to different contexts at low cost:** in many cases more mature technologies are needed to connect the physical and data-driven sides of applications. Validating digital tools in wind farm O&M and in wind turbine manufacturing is a very long process since it needs the input of life cycle operational data. Moreover, too many different turbine technologies need to be modelled – legacy systems as well as rapidly evolving modern technologies – to make the new digital technologies transferable to different contexts at low cost. Well-established data sharing practices within organisations and with third parties, supported by a universal data standard and adequate contractual templates, will help in this regard.

- **Develop the necessary skills combining digitalisation and wind technology expertise:** finally, the ongoing shortage of skills combining wind technology and O&M expertise, with IT development and validation capabilities is a major barrier to the digital transformation of wind. This should be addressed through dedicated wind or electricity digitalisation study programmes in universities and workforce education courses. Rather than reducing the need for human labour, automation and digitalisation are exacerbating the skills shortage. The main factors are limited training and succession planning for skills retention, strict immigration laws preventing access to global talent and loss of expertise due to an ageing workforce[33].

Figure 14 summarises WindEurope's recommendations for the wide uptake of digital applications in wind energy.

32. ENTSO-E, Common Information Model
33. Massachusetts Clean Energy Centre, Massachusetts Offshore Wind Workforce Assessment, 2018

FIGURE 14
Recommendations for the wide uptake of digital applications in wind energy

Understand the benefits

- Universal metrics to quantify the benefits of digitalisation projects
- Knowledge sharing platforms

Develop a universal data standard

- Commonly agreed by all stakeholders
- Going to the necessary level of detail
- Considering and complementing current standards

Establish data sharing

- Within organisations and with third parties
- Supported by a universal wind energy data standard
- Enabled by adequate contractual templates

Validate digital technologies

- Make the technologies transferable to various setups and to different contexts at low cost
- With the support of a universal data standard and well-established data sharing practices

Develop the necessary skills

- Through continuous staff training
- Dedicated energy digitalisation study programmes at universities

ANNEX 1

TABLE OF BENEFITS AND TECHNICAL CHALLENGES IN DIGITAL APPLICATIONS

DIGITAL APPLICATIONS	DIGITAL TOOLS	MAJOR BENEFITS	TECHNICAL CHALLENGES TOWARDS DIGITAL TRANSFORMATION
Forecasting	• Numerical weather prediction • Site mapping and topography • Power conversion algorithms • Electricity price forecasting platforms • SCADA	• Capability for with more comprehensive and refined modelling of weather condition parameters • Wind farms' AEP accurate prediction • Taxonomy of electricity spot price modelling • Better balance of energy supply and demand (system benefit) • Electricity distribution system maintenance to balance losses • Fatigue damage forecasting for critical components	• High uncertainty on stochastic modelling • Undefined input data for modelling and forecasting in a probabilistic framework • Low integration between weather forecasting and electricity loads/prices
Monitoring and control	• Big data learning curves • SCADA • Condition monitoring • Automated bird and bat monitoring • Digital twin • Robust controllers for load reduction (advanced gain scheduling)	• Real time accurate performance overview • Early warning of faults and end-of-life prediction for individual components • O&M optimisation (mathematical optimisation) • Plan strategic O&M modelling (long-term perspective, preventive and predictive) • Wildlife biodiversity protection	• Diversity of assignment/ tasks on and off site • Workforce skills and occupation overlap • Non recorded internal career transition • Lack of IT oriented and trained staff
Workforce Management	• Dedicated workforce management software platforms • Skills/resources data-based visualisation • Machine learning models sorting criticality of jobs	• Task distribution personalised based on technician's skills • Job prioritisation to maximise time and cost efficiency • Advanced workforce evaluation • Real-time technicians' workload scheduling on site • Predictive maintenance strategy based on analytics	• Advanced alarm triggering development to promote predictive maintenance • Poor knowledge of composite material failure mechanisms • Low feasibility of OEM SCADAs integration

DIGITAL APPLICATIONS	DIGITAL TOOLS	MAJOR BENEFITS	TECHNICAL CHALLENGES TOWARDS DIGITAL TRANSFORMATION
Asset health & performance management	• SCADA • Digital twin • Software platforms integrated with monitoring systems • AI predictive maintenance	• Reduce unplanned downtime and increase availability and reliability • Reduce costly emergency repairs thanks to early detection • Improve workforce productivity thanks to maintenance prioritised based on criticality and cost • Standard way to connect machines, data and people to deliver faster time-to-market	• Lack of monitoring-performance-market linked software platforms • Low accuracy of preventive/predictive maintenance models • Missing incentive for the OEMs to provide standardised protocols and tag-naming based on e.g., IEC standards
Staff safety	• Intelligent camera monitoring • Mobile spectrum radio devices • Panic buttons • Real-time stable communication • Image processing drone inspections	• Automated detection of people working in dangerous or no-go areas • Remote inspections prevent accidents	• Cost of radio devices and equipment supporting new communication technologies • Staff training to use advanced digital tools
Spare parts management	• Platform/marketplace for used components • Quality Computerised maintenance management system (CMMS) • Optimal Economic Order Quantity	• Reduced inventory costs • Eliminated service delays due to out-of-stock items • Increased service satisfaction and first-time fix rates	• Absence of critical components labelling methods • No standard work order process
Minimising Environmental Impacts	• Advanced subsea and oversea terrain mapping • Bird and bat detection methods • Noise reduction simulation models	• Wildlife recording • Advanced wind resource assessment related to performance optimisation • Seabed mapping	• Effects on more animals except birds/bats to be investigated • Uncharted ocean topography • Blade and tower vibration impact requires advanced sensing technology
End of life treatment	• Materials modelling • Hybrid models for lifetime extension • Digital twin • Fluid dynamic simulations	• Fatigue damage estimation • Cost reduction strategy • Predictive maintenance • Extend decommissioning	• Poor knowledge of composite materials, blade vibration and icing effects • Unpredicted fatigue damage on offshore farms • High performance uncertainty after reblading or repowering

DIGITAL APPLICATIONS	DIGITAL TOOLS	MAJOR BENEFITS	TECHNICAL CHALLENGES TOWARDS DIGITAL TRANSFORMATION
Wind turbine performance optimisation	• Augmented turbines • Digital Twin • Smart failure prediction • SCADA	• Full visibility to drive down lost production • Identify periods of abnormal operation and non-availability • Assess life extension potential • Event frame-based alarm triggering	• Diversity of turbine model types • Poor knowledge of new composite materials and blade vibration • Compatibility of new sensors with monitoring platforms
Wind farm design optimisation	• Load prediction tools • Advanced weather forecasting • Advanced monitoring • Numerical wake effect models	• Minimised downtime periods • Minimised losses and fatigue damage • Innovative customised farm layout	• Unpredictable turbulence and wake effects • Unique weather conditions and layout at each farm • High cost of software development
O&M optimisation	• Centralised O&M Platform for access by multiple stakeholders • SCADA • Digital reporting and communication • Model based reasoning	• O&M cost reduction • Minimised downtime periods • Lifetime extension • Higher reliability • Automated root cause analysis	• Unpredictable Turbulence and wake effects • Unique weather conditions and layout at each farm
Wind Farm Revenues Optimisation	• Cloud based optimisation models • Forecasted wind data models • Hybrid power output energy demand platforms • Energy market price models	• Stochastic optimisation model to obtain optimal bidding plan • Minimise wind power uncertainties • Balance wind farm lifetime extension-optimal performance	• Complex stochastic and probabilistic models • Both energy market-technical wind skills and knowledge required • Limited data sharing to develop integrated hybrid platforms
Wind turbine design & production	• Digital Twin • 3D printing • Robotics • Order management software platform • Numerical Simulations • Laser and Ultrasonic technologies • Advanced sensing tooling systems	• Standardised and integrated manufacturing approach • Enable a higher degree of customised product designs • Increase tolerance of material fatigue damage and lifetime extension • Better quality and consistency of the product design documentation • Shorter development lead-time to create new product designs	• Ultra-precise and sensitive manufacturing processes • Poor knowledge of composite materials • Complexity of blade geometry

DIGITAL APPLICATIONS	DIGITAL TOOLS	MAJOR BENEFITS	TECHNICAL CHALLENGES TOWARDS DIGITAL TRANSFORMATION
Wind farm construction & logistics	• Aerial photography and topographic mapping software • IoT, Radio frequency identification (data glasses) • Automated Assembly, Guided Vehicles, Vessels & Cranes • Task management software platform	• Standardised and integrated manufacturing approach • Automation of material flows and storage • Digital land survey • Image processing & AI models to inspect hazard or structural damage • High yields of rotation • Efficient handling of small and large loads • Management of complex transportation planning of onshore and offshore installations	• Heavy and sensitive equipment • Incompatibility of procurement systems with Building Information Modelling (BIM) • Cost of automated and autonomous equipment • Unstable offshore platforms
Connectivity	• Internet of Things • 5G/4G • Microsatellite • Mobile spectrum	• Wireless solutions • Private Long-Term Evolution (LTE) coverage on and around the wind farm • Broadband connectivity and next generation voice and video or Augmented Reality capabilities in the field • Centrally operated drones for asset inspection • Advanced remote monitoring (beyond SCADA level) • Higher speed and quality of data and communication	• High cost of new infrastructure and equipment • Absence of basic communication infrastructure onshore
Big data	• IoT Cloud services • Advanced sensing • SCADA • Data reliability assessment tools • Building information models (BIM)	• High data volume and quality for accurate power forecasting and preventive maintenance • Continuous condition overview of critical substructures and foundations • Traceability and improved data quality • Reduce paperwork, manual data recording and analysis	• Need to deploy additional advanced IT methods to post-process data • Time consuming data reliability validation • Low integration between power assessment data and electricity loads and prices • Historical data from over 20 years ago remaining on paper records.

WindEurope is the voice of the wind industry, actively promoting wind power in Europe and worldwide. It has over 400 members with headquarters in more than 35 countries, including the leading wind turbine manufacturers, component suppliers, research institutes, national wind energy associations, developers, contractors, electricity providers, financial institutions, insurance companies and consultants. This combined strength makes WindEurope Europe's largest and most powerful wind energy network.

Rue Belliard 40, 1040 Brussels, Belgium
T +32 2 213 1811 · **F** +32 2 213 1890
windeurope.org