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INFRASTRUCTURE

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Advances in wind and solar operations and maintenance

OPINION PIECE. PLEASE SEE IMPORTANT DISCLOSURES IN THE ENDNOTES.

Current state of wind and solar power

The world's capacity to generate renewable electricity is expanding faster than at any time in the last three decades. The International Energy Agency (IEA) predicts that with 50% more renewable capacity in 2023 than in 2022, ***the next five years will see the fastest growth yet.***

Under existing policies and market conditions:

global renewable power capacity is now expected to grow to

7,300GW

by 2028

with solar PV and wind accounting for

95%

of the expansion.[1]

If we continue along this trajectory, there is a real chance of achieving the goal set by governments at COP28: ***tripling global capacity by 2030.***[2]

Despite continued uncertainty in today's global macro environment, the exponential growth of investment into renewables continues apace. Investment into clean energy is likely to be double the amount going into fossil fuels this year, with spending on track to reach $2 trillion by the end of 2024. This includes investment into renewables, electric vehicles, nuclear power, grids, storage, low-emissions fuels, efficiency improvements and heat pumps.[3]

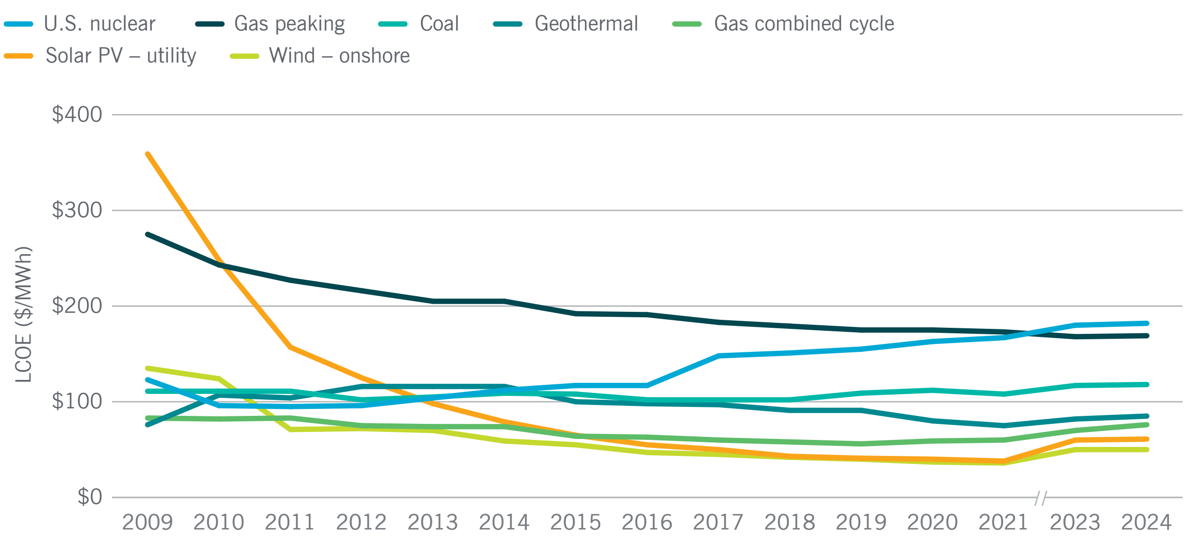
Lazard's levelized cost of electricity (LCOE) analysis shows significant historical cost declines for utility-scale renewable energy generation technologies from 2009 to 2021 (see Figure 1). Despite recent upticks in the LCOE from wind and solar over the last couple of years, these still remain a cheaper source of energy generation than conventional fossil fuels, and the competitive cost of renewables is driving investment.

Solar PV is leading the transformation of the energy sector, with more money currently being channelled into the sector than all other electricity generation technologies combined. The IEA predicts that investment in solar PV is set to grow to $500 billion in 2024, as falling module prices spur new investments.[4] Solar PV and onshore wind deployment in the U.S., the EU, India and Brazil is expected to more than double through to 2028, compared with the last five years. In 2023 solar PV module prices declined by almost 50% from the previous year, and cost reductions and fast deployment are expected to continue. In contrast, the wind industry (outside of China) is facing a more challenging environment due to a combination of ongoing supply chain disruption, higher costs and long permitting timelines.[5]

> **"The rise in clean energy spending is underpinned by strong economics, by continued cost reductions and by considerations of energy security. But there is a strong element of industrial policy, too, as major economies compete for advantage in new clean energy supply chains."**
>
> **—IEA Executive Director Fatih Birol[6]**

Figure 1: Levelized cost of electricity comparison[7]

Selected historical average LCOE values



Data source: Lazard.

Role of O&M in lifetime and efficiency of renewable energy systems

The main economic advantage of wind and solar PV energy is that its production has no marginal cost of input. However, the operations and maintenance (O&M) costs of wind and solar farms make up a significant portion of the total cost over a project's lifecycle. The scale of renewable energy projects is expanding to keep up with increasing demand for renewable energy, with larger turbines, better solar modules and bigger project sites. With this, comes the increasing need to innovate; advances in O&M will reduce costs over time and enable O&M teams to deliver efficient and low-cost renewable energy to consumers.

O&M is key for increasing the reliability, efficiency and lifetime of wind and solar plants. Keeping equipment working as close as possible to full-spec for the longest possible time ensures that the most energy and economic value is delivered from the project. There are many exciting opportunities to deploy new technologies such as robotics, drones, and AI programs that can increase the efficiency of wind and solar farms and help keep O&M costs down.

Operations include the day-to-day activities that ensure optimal performance, such as the early detection of anomalies in equipment via sensors and software. Data can be analysed to optimise operational factors, to reduce strain on equipment and improve energy output. The early detection of issues prevents more costly repairs later on.

Maintenance includes regular and preventative actions to keep equipment working properly and to reduce repair costs. Maintenance activities must be done quickly and efficiently to reduce plant downtime. Maintenance must also be planned carefully and executed efficiently as onsite teams, heavy lift cranes (in the case of wind farms), and specialised service vessels (in the case of offshore wind), can be very expensive to deploy for extended periods of time.

This paper provides an overview of key O&M activities and how these are being improved through learning and new technologies to deliver better technical performance and profitability from wind and solar assets.

Wind developments

A global surge in the adoption of wind energy and an increasing number of operational wind turbines, could present a challenge for O&M teams.[8] In addition to being more widespread, turbines are also getting steadily larger. Manufacturers are planning an extensive rollout of new-generation offshore wind turbines with a capacity rating of over 10 MW. Most offshore wind farms commissioned after 2023 will use equipment of this size, with 15 MW models already contracted for delivery in 2025.[9] This rapid evolution of models with unique components can make it more difficult for original equipment manufacturers (OEMs) to deliver sufficient supplies of blades and other equipment where they are needed. An emphasis on serialisation and interchangeability can help to deliver more efficient maintenance. To properly service these larger fleets of complex machines, often in remote locations, O&M teams are using innovative monitoring, inspection, and rectification techniques.

Predictive maintenance

Machine learning models can forecast the remaining useful life of critical components of wind farms. This allows O&M teams to proactively address issues before they escalate, minimising downtime and repair costs.[10] By using more proactive maintenance strategies, teams can identify mechanical component degradation before it leads to significant damage or failure. This also means that repairs can be carried out during periods of low wind or scheduled downtime, reducing the impact on energy production.[11]

Sensors for real time monitoring

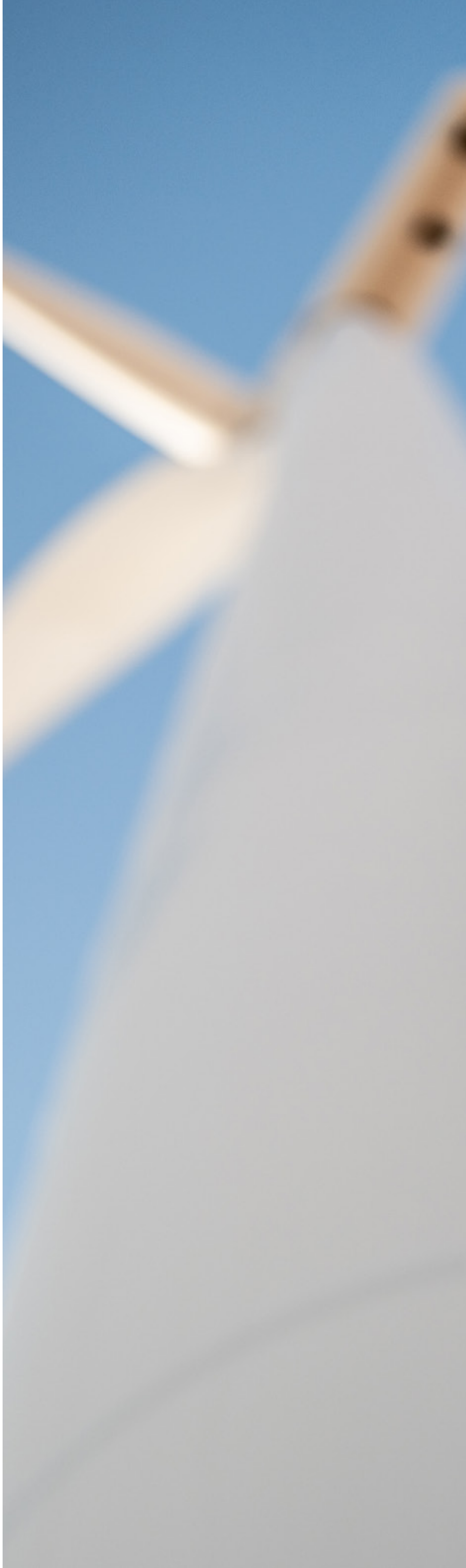
Condition monitoring can be used to detect changes in wind turbine behaviour, predicting developing faults to minimise performance degradation and costly repairs. Vibration monitoring is the most commonly used technique in wind turbine condition monitoring, as most damages in rotating machinery are reflected as higher vibration levels at frequencies specific to a developing fault.

The failure of structural components such as foundations, blades and towers can significantly affect the operational costs of a wind turbine. Offshore wind turbines in particular are exposed to harsh environments, including extreme wind speed, wave load, stress and corrosion. The monitoring of structural components is essential to reduce maintenance costs and avoid costly failures.

Sensors are used for monitoring the structural health of wind turbines and for monitoring drivetrain components, such as shafts, bearings, gearboxes and generators.[12]

AI blade inspection – failure prediction

AI technology can help detect defects and critical blade conditions through the automated analysis of inspection data. This can provide higher quality results faster, and at a lower cost than human-based detection and analysis. AI-based blade analysis platforms are able to reduce damage detection and condition assessment costs by 90%.[13]



The AI-based inspection and analysis of blades contains several steps:

1. Data is gathered by experienced drone and/or ground-based technicians. This needs to be high quality image data to identify and classify defects.
2. The data from each blade is uploaded into a secure, encrypted cloud-based platform.
3. Uploaded data is processed by an AI engine-based software platform, frame by frame, to find and classify blade impairments.
4. The results can then be analysed.

Robotics and drones

Drone data for blade erosion – annual energy production (AEP) loss calculation

The degradation of turbine blade surfaces, particularly leading-edge erosion, can lead to operational risks. O&M teams can combine existing drone inspection metadata with a custom aerodynamic model of a specific wind turbine to calculate aerodynamic performance with and without the identified blade damage. These simulations can then be compared to find the impact of the real-world blade conditions on the annual energy production (AEP) of the turbine. This method uses a set of aerodynamic engineering calculations based on the industry-standard Blade Element Momentum (BEM) approach. A software tool can provide a library of turbine-specific BEM models, using the details of each specific blade and turbine model in question.[14]

Sanding, cleaning and restoring with robots

Leading-edge blade damage can compromise the aerodynamic performance of a wind turbine by up to 3% and can lead to blade failure if not addressed. Blade damage caused by rain erosion is currently a significant problem and likely to become more so as blade lengths increase. Repairs usually require skilled manual work hundreds of metres above the ground, using specialist tools, polymer coatings and substrate materials. Blade repair robots can use high-resolution cameras, laser scanners and repair tools operated by a flexible arm to sand, clean and restore damaged blades. The robots can also be programmed with the original blade profile so that they restore the blade to the exact profile from the design. Technicians monitor the robot on-screen, either on-site or remotely.[15]

Remote monitoring and control

Leveraging vibration data for energy management

For the structural health monitoring of wind turbines, O&M teams must collect vibration data to detect developing faults.[16] Leveraging vibration data, alongside advanced data analysis, statistical techniques and machine learning models, has the potential not only to model, but also predict the nuanced behaviour of various wind turbine components. By continuous learning from operational data, machine learning algorithms can become skilled at identifying patterns suggesting likely failures or deviations from optimal performance.[17]

Advances in wind turbine condition monitoring and wake optimisation

Advanced condition monitoring systems and wake optimisation strategies can improve the operational efficiency and economic viability of wind farms, particularly those offshore. The current LCOE of offshore wind energy is still higher than that of onshore wind, largely because of the higher logistical complexity and capex costs of offshore wind farms. Increased use of condition monitoring offshore can improve the reliability of wind turbines, potentially reduce the need to access offshore turbines, and help increase the economic competitiveness of the wind farm.

Wake losses can be minimised by optimising the wind farm layout and by applying innovative control methods such as wake steering: misaligning upstream wind turbines with the wind to deflect their wakes from downstream turbines, decreasing the internal wake losses and increasing the overall wind farm output. Wind farm wakes can be characterised using measurement equipment, such as scanning or nacelle lidars. These can help analyse turbulence intensity, wake width and velocity deficit, as well as interactions between multiple wind turbines.

Equipment used in the condition monitoring of wind turbines can include high-end accelerometers for vibration sensing, data acquisition systems capable of long-duration (> 2min) multichannel measurements at high sampling rates (> 30kHz), and edge computing devices for local data processing, such as data quality checks and low computational cost calculations. This allows O&M teams to track the degradation in the rotating components and alarms can then be triggered to notify the maintenance teams when specific asset components are degraded.[18]

Service operations vessels (SOVs) for offshore wind

Larger, more efficient, and better equipped service operation vessels are being developed. These allow O&M technicians to live out at sea for weeks at a time. They live aboard and stay out at site in rotations, enabling more efficient maintenance of offshore wind farms far out at sea.

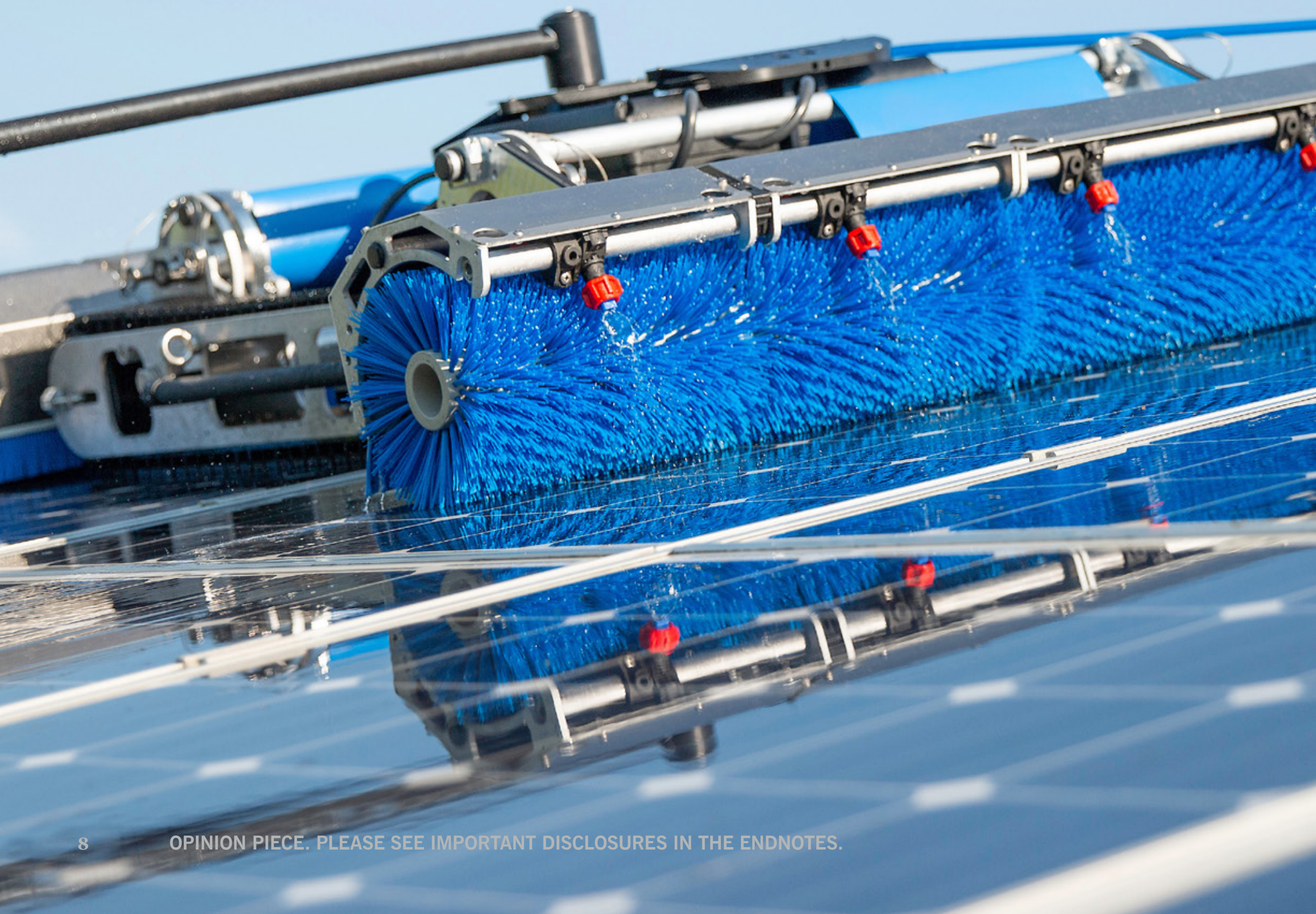
Ørsted's Wind of Change is the first hybrid battery DC network DPII SOV for wind farm maintenance and will serve in the Borkum Riffgrund 1 and 2 and Gode Wind 1 and 2 wind farms off the coast of Germany. Wind of Change is one of the biggest SOVs servicing wind turbines. It is equipped with a 'heave compensated gangway' system to provide technicians with continuous safe access to turbines, and a 3D crane for handling cargo and materials between the vessel and the turbines. There are two batteries onboard, resulting in a significant reduction in fuel consumption and exhaust emissions.[19] The vessel also has a helipad for more flexible crew exchange if needed. It can support up to 90 people with living quarters, a cinema room, a gym, meeting rooms, and conference rooms so that it can be a fully functioning living space and workspace.

The world's first e-methanol-fueled SOV was launched at Cemre Shipyard in Turkey in June 2024. The NB1094 SOV will be powered by batteries and dual-fuel engines capable of sailing on renewable e-methanol, produced from wind energy and biogenic carbon, which should lead to a yearly emission reduction of approximately 4,500 tonnes of CO_2. The Danish-flagged vessel will start servicing the world's largest offshore wind farm — Hornsea 2 — located off the UK's Yorkshire coast in the North Sea. In July 2023, Esvagt and Ørsted signed an agreement for a second methanol-powered SOV, which is a sister vessel to the world's first methanol-powered ship. The launch of a second vessel is planned for 2026, operating out of Ørsted's UK east coast hub on a 10-year contract.[20]

Photo: Marine Traffic.

Solar developments

With the solar industry expected to soar over the next few years and individual solar farms now covering tens of km^2, more efficient, effective and sophisticated monitoring and configurable systems are needed.[21] Solar operations and maintenance is becoming an increasingly crucial part of the solar power market value chain globally[22] and O&M is the largest part of a utility-scale solar asset's post-construction budget. A significant portion of solar O&M used to be performed manually. However, with the growing scale, size and number of solar projects, manual O&M has become costly, with labour costs typically accounting for 60–70% of O&M.[23]



Cleaning technologies

Innovation to reduce manual labour cost

The regular cleaning of solar panels is critical for removing impurities such as dust, lichen or bird droppings, which can reduce panels' ability to catch sunlight efficiently. Traditionally, module cleaning is a particularly labour-intensive task, and O&M teams are increasingly integrating digital technology and automation to reduce time and labour costs and to increase efficiency. The solar industry is seeing a huge uptake in semi-automated and fully automated robotics for panel cleaning. These are now being adopted for large utility-scale projects, at competitive prices. However, while automation can reduce the need for manpower, skilled technicians and engineers are still necessary for managing these tools effectively.

In dry regions, which are popular sites for solar installations, frequent cleaning is vital and waterless solutions are sometimes more practical. Various mechanical, coating and electrostatic techniques are currently used. These include air-blowing, water-blowing and ultrasonic vibration methods.

Anti soiling coating involves applying a thin film of hydrophilic and hydrophobic nanoparticles on the solar panel surface. Hydrophobic coating makes water roll off the surface of the panel, carrying dust and other impurities along with it, while hydrophilic coating reduces the deposition of dirt through a photo catalytic reaction. Coating keeps the panel surface clean for longer periods, especially when combined with mechanical cleaning, but is still in the early stages of development and is still relatively expensive, with a payback period of approximately five to six years. However it is expected to increase in reliability, effectiveness and to become more cost-competitive.

Electrostatic cleaning methods include the electrodynamic screen cleaning technique, which uses electric curtain boards to expel dust from the surface of the panel. Another technique involves repelling dust particles by using an electrostatic induction charge. These technologies also need further research and development before they are taken up on a large scale. Adoption of each of these techniques described above will also depend on the geography, climate, accessibility and budget for each solar site.[24]

Monitoring systems

Condition monitoring involves sifting through and analysing substantial amounts of data from across the plant in normal and abnormal operation. The output from condition monitoring can aid the identification of faulty modules, calculations on module efficiency and compliance to grid standards. Remote condition monitoring software can help O&M teams with the planning of strategies and corrective maintenance plans. Condition monitoring systems can identify issues such as a dirty inverter filter panels, faulty PV connecters or malfunctioning inverters. Being able to do this remotely without sending a technician to the site helps to reduce costs, as well as potential downtime.[25]

Energy storage

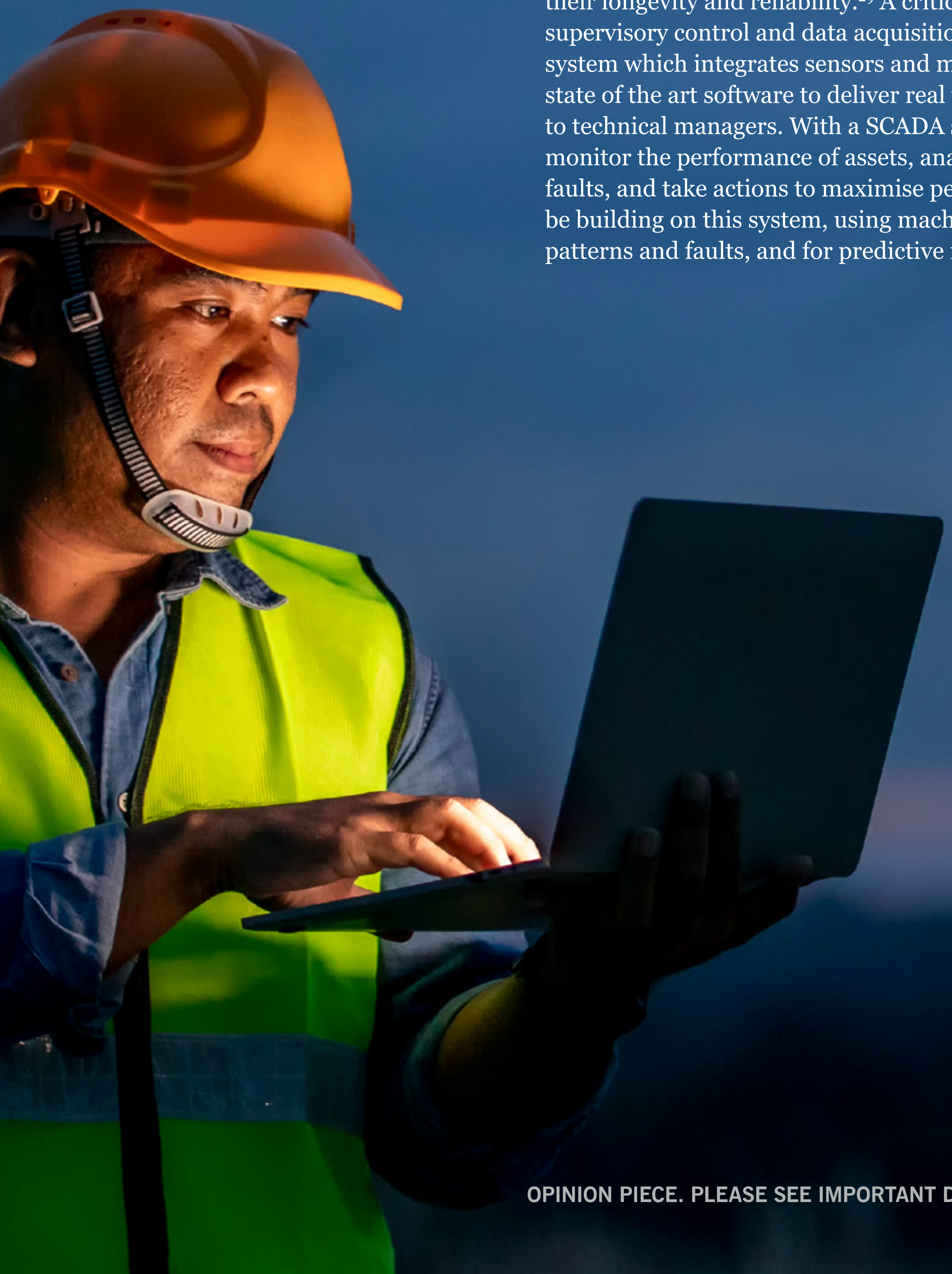
A lack of investment in grids and electricity storage has been a significant constraint on the clean energy transition, as these are necessary to maximise energy usage and to ensure a more consistent energy supply. However, spending on grids is growing and expected to reach $400 billion globally in 2024, a significant increase from its circa $300 billion annual constant between 2015 and 2021. Meanwhile, investments in battery storage are set to soar to $54 billion in 2024 as battery costs fall.[26]

More advanced battery technologies are being developed. These include improved lithium-ion cells and flow batteries, specifically designed for solar energy storage. These batteries can provide higher energy density, a longer lifespan, and improved charging and discharging capabilities. This should enable O&M teams to maximise the use of stored energy based on demand, grid conditions, or time-of-use pricing, leading to cost savings and increased energy efficiency.[27] IoT technologies can be used to measure and control the status of energy stores remotely, enabling remote troubleshooting and problem-solving.[28]

As governments and utilities around the world recognise the value and potential of energy storage in supporting renewable energy integration and grid stability, we should see the introduction of improved automation, operational technologies and other techniques to maximize the impact of this growing storage fleet.

Innovation in management

In the fast-paced realm of wind and solar energy management, the complexities of increasingly large wind and solar farms pose formidable challenges for O&M teams. The sheer size of these assets requires innovative, adaptive and efficient maintenance practices to ensure their longevity and reliability.[29] A critical tool for asset managers is the supervisory control and data acquisition (SCADA) system. This is a system which integrates sensors and monitoring equipment on site with state of the art software to deliver real time and historical data analysis to technical managers. With a SCADA system, it’s possible to remotely monitor the performance of assets, analyse production trends, identify faults, and take actions to maximise performance. O&M teams should be building on this system, using machine learning and AI to mine for patterns and faults, and for predictive maintenance strategies.



Digital twin technology

Today's wind farms can cover areas of over 400 km^2, while solar farms can cover tens of km^2. Without real-time oversight of all these power plants, it can be difficult to ensure they run smoothly, without faults and costly downtime. Digital twins can address this issue, helping O&M teams to manage assets across large areas.[30]

Digital twins are digital replicas of physical objects, offering real-time monitoring. To create a digital twin, engineers collect data from sensors, cameras and other sources that monitor physical objects. They feed this data into digital twin software that generates a virtual model of the object, which accurately represents the behaviour and characteristics of the actual system. For solar, digital twins can facilitate inspection, predictive maintenance and performance solutions. For wind, they can help with extreme weather impact reduction and can diagnose faults remotely.

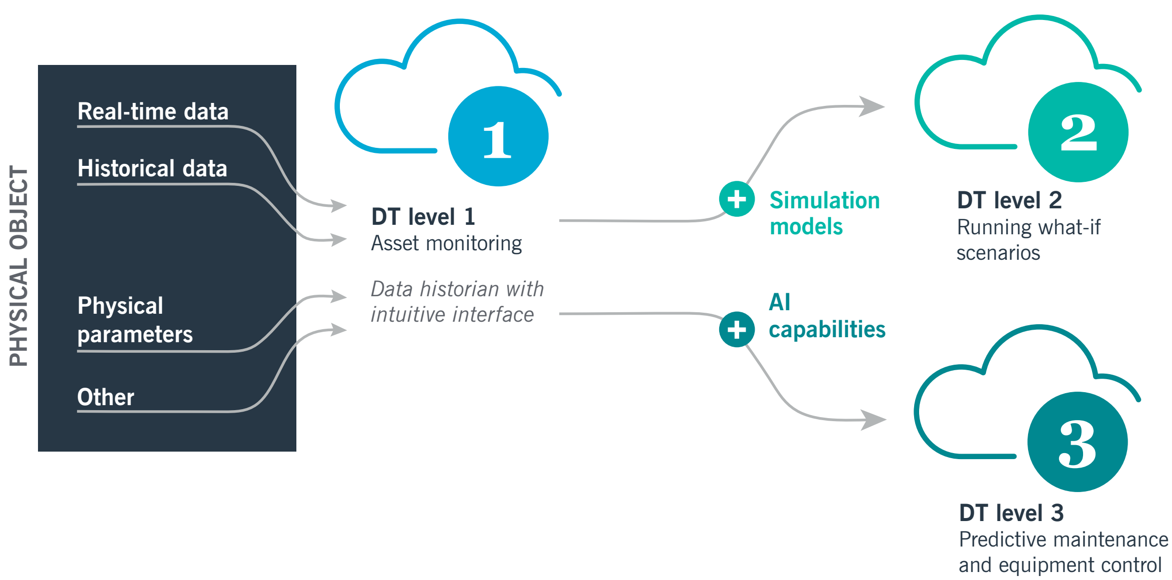
Digital twins operate at three levels:

- Basic – gathering data
- Intermediate – generating 'what-if' scenarios
- Advanced – using AI to detect deviation in an asset's behaviour

Equipment strategy

The solar industry has suffered supply chain issues since the Covid-19 pandemic. Even as components become more reliably available, managing panel, inverter and other equipment inventory to meet preventative and emergency maintenance needs across numerous sites is challenging. Ten different projects might need inventory from 20 different panel and inverter suppliers, up to 100 different types of parts and 200+ spares to ensure swift replacements and to avoid costly downtime.

Figure 2: Digital twin models can monitor physical objects, optimize their operations and fully control their behavior[31]



Source: SoftEQ.

Even if asset owners outsource to a third-party spare parts provider, they still have to contract separately for each project. This makes factoring equipment needs into O&M strategy a sensible option. By standardising similar equipment across multiple projects, asset owners can make bulk purchases of fewer types of panels and inverters to help with spare parts and inventory challenges. If outsourcing to an O&M provider, they can apply a master service agreement to cover all projects, thereby reducing the time and effort required for contract negotiations. This can also ensure that projects are being built with the highest quality components, as well as reducing the need for training and knowledge transfer, as technicians are servicing fewer types of equipment.[32]

Virtual and Augmented reality

Virtual and augmented reality (VR and AR) applications can increase both safety and efficiency for wind and solar farms. AR combines digital and physical elements to create artificial environment focusing on real-time interaction in a 3D space, while VR immerses users in simulated alternate realities with sensory experiences. These technologies can be used for training, modelling, visualisation and remote operation with complex information structures and concepts. They can make assembly and design more efficient, while allowing employees to interact with virtual models and reduce the need for physical interfaces.

Using AR for operation and asset management allows technicians to view the internal components of complex equipment and can improve the efficiency of workers in the field, as well as reducing the risks associated with the physical operation of wind and solar farms. AR can also help technicians onsite identify small faults which they may otherwise overlook.

AR and VR is also increasingly being used as a training tool for engineers and technicians in the renewable energy sector. For example, it can be used as a digital twin or simulated model, allowing workers to experience how a wind turbine will behave during a storm. This can improve the skills needed for high-risk operations, while offering a more affordable and safe solution.

As AR and VR continue to advance, they have the potential to enhance the wind and solar industries, especially in the areas of training and remote operations. Researchers can test out different scenarios and make critical decisions safely, without wasting resources. VR and AR can also help improve teamwork, communication, inspection and maintenance, leading to safer and more efficient operations and reduced costs.[33]

Safety improvements

The regular maintenance of solar and wind farms should improve safety conditions for workers. Many of the new technologies described in the sections above can improve safety. Drones and robotics are increasingly used for more dangerous tasks, while AR and VR can reduce safety risks by improving skills and enabling remote work.

Wind turbines and solar farms are often exposed to hazardous environments. AR and VR technologies can replace verbal and nonverbal communication and notify people of hazard zones. These technologies can also help engineers and technicians to perform better inspections, as well as to identify emerging threats and provide safe exit directions. Solutions can be displayed in real time, making them particularly valuable for workers in hazardous areas.[34]

Examples from Nuveen Infrastructure

SkySpecs is supporting Nuveen with SCADA[35] Analytics. Using wind-specific data, technology and robotics, the aim is to keep wind turbines running smoothly, efficiently and with minimal downtime.[36] This is achieved by combining multiple data sources with intelligent analytics to optimise assets. This includes: real time monitoring, data acquisition and logging, alarms and alerts, reporting and analysis. The team uses AI to analyse the data and to generate reports and deliver insights to help with decision making. This performance management and monitoring allows remote diagnostics and analysis, reducing the need for site visits.

Figure 3: Examples of value generation through Nuveen and SkySpecs teamwork[37]

Early detection of generator bearing issues in a hot environment	Detection of underperformance on a complex site (icing, wake)	Early detection of a blade bearing issue, proactive replacement
BENEFIT >250K Euros saved by each avoided generator failure	**BENEFIT** Focus O&M efforts on issues where revenue can be gained	**BENEFIT** >50K Euros saved by avoiding downtime

Source: Nuveen, SkySpecs.

Outlook and conclusions

As the renewable energy sector grows and the scale of wind and solar farms expands, effective O&M becomes increasingly important. Advances in O&M are already reducing costs and allowing those in the energy sector to generate power from renewable sources more reliably and efficiently.

Predictive maintenance allows O&M teams to proactively address issues before they escalate, minimising downtime and repair costs. AI, robotics, and drone technology can help detect defects through the automated analysis of inspection data. This can provide higher quality results faster, and at a lower cost than human-based detection and analysis. By continuous learning from operational data, machine learning algorithms can become skilled at identifying patterns suggesting likely failures or deviations from optimal performance.

These technologies are improving all the time, helping reduce costs, deliver higher outputs, extend the lifespan of wind and solar farms, improve the efficiency of operations and increase safety and job conditions. All of these improvements help the delivery of cheaper and more reliable renewable energy for consumers and better economic returns for project owners.

Utility-scale wind and solar has come a long way in recent years. As the industry continues to evolve, O&M best practices and technology will too, paving the way for asset owners to deploy smarter strategies and achieve greater performance.[38] There is huge potential for future innovation and improvement in O&M for the wind and solar sectors. This will continue to boost efficiency and to drive investment in and deployment of renewable energy.

For more information about our clean energy infrastructure strategy please visit nuveen.com/clean energy.

Endnotes

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