Wind energy beyond the cloud

Why Edge AI is key to unlocking the full potential of wind power

Executive summary

Wind power's time has come.

As reported in [Capgemini's 26th World Energy Markets Observatory (WEMO)](), wind power has seen 10% growth rates in recent years, and reached 30% of EU electricity generation.

As part of its ascendence, the wind energy sector has invested heavily in cloud-based data analytics and AI. In doing so, it anticipated big gains from real-time optimized performance, reduced downtime, and extended turbine lifespan – and ultimately new tech-style, service oriented business models where wind turbines sell digital services and data-driven insights.

But the industry has not seen this promised value. Why?

Many exciting AI and Machine Learning models could deliver the promised value to wind, as this paper will show in Part 1. But – for reasons we will discuss – few such models are suited to running in the cloud. At the same time, the rapid growth of data centers needed for the cloud is creating environmental concerns.

Moving from a centralized cloud approach to an Edge approach – where wind turbines deploy computing capabilities and AI models on the turbine itself – could unlock a whole host of benefits to both OEMs and developers. It could also create entirely new business models. We will discuss both in Part 2.

Part 1:
Why cloud-based analytics have underdelivered for wind energy

Over the last decade, wind energy developers and wind turbine manufacturers have invested heavily in data analytics and AI.

Countless companies and studies have claimed digital technologies (e.g. AI/ML, IoT, and predictive analytics) will detect underperformance, reduce downtime, prevent faults, increase lifespan, and so on, enabling new levels of efficiency, and oil & gas profit levels.

As a consequence, wind energy players have invested massively in large data/IT infrastructures, cloud solutions, and digital services, in order to gather terabits of data on wind speed, air conditions, blade speed and angle, power output, vibrations, temperature, etc, from thousands of wind turbines equipped with hundreds of sensors.

Have these digital investments delivered?

The increase in data has certainly grown research into applying analytics, AI & ML to wind energy. A recent study[1] shows exponential growth in the number of publications from 2000 to 2022.

And this research has created valuable models for optimizing energy generation, such as wind farm control (e.g. wake adjustments, alarms, control systems), wind speed prediction, and the monitoring of electrical equipment, mechanical parts, and faults.[3],[2]

However, this promise in the lab has rarely led to large scale real-life deployments. A few rare, published successes include a 2.7% energy production increase from active control of yaw misalignment[3], and increased wind capacity per area of land of up to 22%[4],[5] from better wake steering and optimized windfarm layouts. But most studies do not mention real world impact.

Data released by industry tells a similar story. Most big players have invested in digital optimization. Publicly available data on these is limited, but published results vary from a 1% Annual Energy Production (AEP) increase for specific wake steering solutions[6] to up to 5% for more advanced features[7]. OEMs assert bigger numbers, including claims of up to 10% in Annual Energy Production[8].
Even the best results – and few are hitting these numbers – are not the transformational figures that were hoped for.

So, what is not working?

Two main problems hinder progress. The first is that all these promising academic models run too slowly and require too much processing power. Wind turbines must send sensor data back to a cloud, run a model, return the data, and act on it. To offer real-time optimization, they may need to do this thousands of times, across thousands of sensors and control mechanisms.

Reviews of models highlight that, to deliver at scale, they need to significantly reduce processing time, and use faster communication technologies (like 5G) between the turbine and the cloud. Such reviews also identify a need for better protection against cyberattacks.

As such, the deployment of promising models is still mostly at the Proof of Concept (POC) or small scale deployment stage.

Is data intelligence being scaled the right way in the wind energy sector?

The second problem is that wind professionals are now overwhelmed with data.

Today, around 350,000 wind turbines are installed globally[9]. This is expected to double by 2030[10]. Each smart turbine contains over 300 sensors, continuously transmitting over 200 gigabytes of data per day[11]. Most of this data is boring, reporting at high frequency that everything is normal. Sending all this information back to the cloud is wasteful and expensive.

The facts are clear. Data can enable more efficient wind energy generation. The industry has a dense academic knowledge base and hundreds of promising models. But there is a real challenge when it comes to scaling and industrializing those models. At the same time, too much data is being accumulated in data centers, with very little value produced from it.

Part 2:
Enabling decentralized control through Edge AI

By switching to distributed intelligence, with Edge computing, wind can finally realize the promised benefits of these many AI/ML models, not just individually, but the compounding returns that come from combining them at scale.

Wind is all about decentralized energy generation. It should also consider decentralizing its intelligence – enabling the turbines themselves to make real time decisions, instead of building big centralized ‘brains’ to supervise everything from data centers.

Edge AI enables this shift. It puts computational power and AI/ML models on the turbine, allowing them to collect data from their local environment, run models, and dynamically adjust to optimize generation. This all happens with minimal cost, whilst removing risks from network and connectivity issues.

The wind turbine might not be able to run the largest and most sophisticated models at the Edge, but usually there is no need. By training Edge models to identify normal operation, most day-to-day optimizations can be performed, whilst notably unusual patterns can be flagged to the cloud.

Wind turbines are also particularly suited to Edge technology as, although there are many types of turbine, they have fairly similar architectures, working principles, and issues.

Cloud will not disappear, of course, but wind will shift towards hybrid computing models. Data will still be backhauled to centralized computing units for non-urgent tasks, like developing and training new models. And a cloud based management system will still be needed to oversee and control the wind turbines, enabling virtual power plants (VPPs) which can also optimize operations at a portfolio level. But AI models themselves will mostly run at the Edge, delivering real time optimization.

Edge AI has already found many use cases in consumer electronics and high frequency manufacturing processes. Now it could usher in a new era of wind energy, resolving the complexity of managing ever-growing numbers of turbines in diverse settings, whilst maximizing each individual asset’s profitability. And the cherry on the cake is that Edge AI also reduces carbon emissions, by removing a tremendous amount of unnecessary data transfer and processing.

The major breakthrough will come from switching from a group of wind turbines to a network of intelligent wind power generators.

The benefits of Edge AI

At the turbine level:

- **Near real-time issue prediction and detection:** pre-trained algorithms will offer real-time detection of 'normal' vs 'unusual' operation, allowing improved responsiveness to turbine underperformance. Edge algorithms could also integrate data from local IoT to monitor other signals (e.g. component fatigue, corrosion, etc.)

- **Dynamic contextualization and adjustments:** using local sensor data (e.g. local weather, data, or grid signals), the turbine can dynamically adapt its parameters to optimize its production.

- **Asset security/data privacy:** by processing most of the raw data inside the turbine, the amount of data flowing outside the asset (and beyond the wind farm) is limited and hence more secure.

- **Robust against network/connectivity issues:** processing at the Edge allows the turbine to reduce its dependence on network quality and communication with control centers, reducing downtime from network issues.

At the global fleet level:

- **The industrialization of data analytics and AI:** unlocking value from 10+ years of data science research and investments from asset owners and OEMs.
- **Turbine interference and interdependence management:** minimizing interference (i.e. wake effect) between turbines.
- **Sensor redundancy and data consistency:** integrating data from the surrounding turbines to check consistency with the turbine's own sensor data, or ensure continuity of operation in the case of sensor failure (e.g. working with the closest turbine's anemometer data if needed).
- **Self-optimized VPPs and services to the grid:** turning a wind farm into a generation unit, able to couple with storage systems and act as a controllable asset to optimize revenues, manage load balancing, avoid penalties, and provide services to the grid.
- **Weather anticipation:** generating better forecasts of wind speed and direction by using upstream wind turbine sensor data (i.e. wind direction, speed, temperature).
- **Contained infrastructure size and cost:** by reducing raw data flows to/from assets to servers, Edge AI constrains infrastructure costs and size, reducing required network bandwidth and storage.
- **Federated learning:** enabling turbines to integrate new anomaly detection capabilities (developed by other wind turbines) with their own sensors through machine learning. This is one of the most advanced features enabled by Edge computing and IoT networks ('IoT swarms') that would give turbines autonomous and collective 'learning' capabilities. Capgemini has developed a specific demonstrator of this technology, dedicated to wind farms, in the framework of the OASEES project.
- **Smaller carbon footprint:** removing the daily upload and storage of hundreds of terabytes of raw data and time series would immediately offset data storage and data management carbon emissions.

How Edge AI will change business models

The Edge is not just a technological improvement, it will have dramatic implications for wind industry business models.

Over the last decade, **turbine manufacturers** have developed a wider range of products and scaled designs to create powerful offshore turbines (15MW and beyond). This has led to increased complexity in design and manufacturing, just as demand for wind power is surging. As a result, wind OEMs face reliability issues and backlogs, and suffer from inflated warranty and service maintenance costs.

This is leading to a focus on fewer product variants, and better fleet availability and reliability[12]. Edge AI will support this strategy switch. It sets new standards for availability and reliability, and introduces features that enhance energy output by intelligently optimizing it based on environmental conditions, rather than simply adding larger blades to turbines.

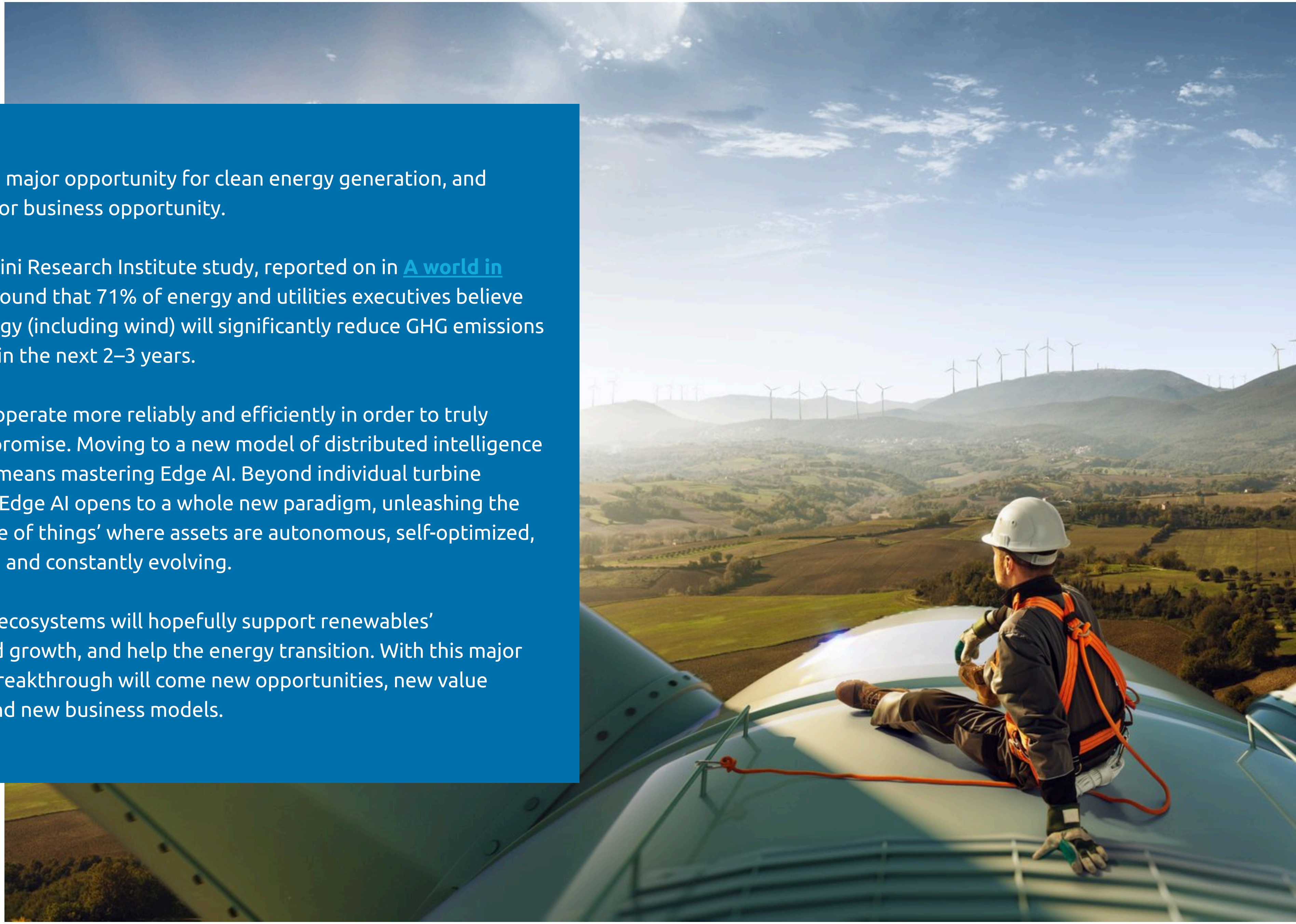
Turbines may soon differentiate based on CPU power and intelligent software packages, similar to the smartphone industry. Manufacturers could release a single turbine model with varying CPU power and software packages, offering different levels of intelligence, autonomy, and business insights.

We may soon see turbines differentiate based on CPU power and intelligent software packages (rather than just physical design), as in the smartphone industry.

This will have further implications for OEMs. They will need to evolve to manage new activities, like CPU obsolescence, and software lifecycle management – as other digitizing industries have. Software maintenance services will become critical, as a turbine's integrity and performance will strongly depend on its CPU condition monitoring and software updates.

Energy developers will also benefit from these changes and see their business models evolve – as Edge AI enables them to manage clusters created by asset aggregation and hybridization, managing energy production through VPPs, maximizing power generation and monetization at the portfolio level. They might also give up developing algorithms to improve turbine performance (leaving this to OEMs). Instead, they might focus more on models that maximize the whole portfolio value, by improving energy production from various interdependent assets that collaborate on grid management and responding to market signals.

Conclusion



Wind power is a major opportunity for clean energy generation, and therefore a major business opportunity.

A 2024 Capgemini Research Institute study, reported on in A world in balance 2024, found that 71% of energy and utilities executives believe renewable energy (including wind) will significantly reduce GHG emissions in their sectors in the next 2–3 years.

But wind must operate more reliably and efficiently in order to truly deliver on this promise. Moving to a new model of distributed intelligence for wind farms means mastering Edge AI. Beyond individual turbine improvements, Edge AI opens to a whole new paradigm, unleashing the real 'intelligence of things' where assets are autonomous, self-optimized, interconnected, and constantly evolving.

Creating smart ecosystems will hopefully support renewables' profitability and growth, and help the energy transition. With this major technological breakthrough will come new opportunities, new value propositions, and new business models.

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