Grand Challenges in the Digitalisation of Wind Energy

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Abstract. The availability of large amounts of data is starting to impact how the wind energy community works. From turbine design to plant layout, construction, commissioning, and maintenance and operations, new processes and business models are springing up. This is the process of digitalisation, and it promises improved efficiency and greater insight, ultimately leading to increased energy capture and significant savings for wind plant operators, thus reducing the levelized cost of energy. Digitalisation is also impacting research, where it is both easing and speeding up collaboration, as well as making research results more accessible. This is the basis for innovations that can be taken up by end users. But digitalisation faces barriers. This paper uses a literature survey and the results from an expert elicitation to identify three common industry-wide barriers to the digitalisation of wind energy. Comparison with other networked industries and past and ongoing initiatives to foster digitalisation show that these barriers can only be overcome by wide-reaching strategic efforts, and so we see these as “Grand Challenges” in the digitalisation of wind energy. They are, first, ~~the need to create reusable~~ creating FAIR data frameworks; secondly, ~~the need to connect people to~~ connecting people and data to foster innovation; and finally, ~~the need to enable~~ enabling collaboration and competition between organisations. The Grand Challenges in the digitalisation of wind energy thus include a mix of technical~~and cultural~~, cultural, and business aspects that will need collaboration between businesses, academia, and government to solve. Working to mitigate them is the beginning of a dynamic process that will position wind energy as an essential part of a global clean energy future.

1 Introduction

The global green transition is the process of changing our technological base and consumption patterns to reduce and ultimately reverse anthropogenic climate change. An integral part of the green transition is the ~~adoption of very high levels of renewable energy sources,~~ energy transition, which is the change in energy generation and consumption away from fossil fuels towards renewable energy from sources such as wind energy, coupled with increased electrification (**?**).

~~In an article in *Science*, **?** discussed how to secure a competitive wind energy price in the energy market, and positioning wind as~~

1.1 What are “Grand Challenges”?

In order for wind to be one of the primary sources of ~~the world’s electricity generation by 2050. Their~~ electricity generation in 2050, **?** argue in their paper, “Grand challenges in the science of wind energy~~,”identified~~”, that the wind energy sector must address three high-level ~~Grand Challenges~~issues, which they describe as “Grand Challenges”:

1. Improved understanding of atmospheric and wind power plant flow physics
2. Aerodynamics, structural dynamics, and offshore wind hydrodynamics of enlarged wind turbines, and
3. Systems science for the integration of wind power plants into the future electricity grid.

~~These Grand Challengesare similar to the long-term research challenges in wind energy identified by **?**. However, a response to the Veers article pointed out that there were other important Grand Challenges~~

Several things are clear from the “Grand Challenges” paper and other discussions of the future direction for wind energy (e.g., **??**). First, there are also important challenges related to environmental and ecological impacts (**??**), as well as social, “territorial and institutional dimensions” (**?**). Second, [1] ~~and there have been other discussions since about what the Grand Challenges really are and how the international wind energy community is responding to them (e.g., **?**).~~

1.2 ~~The role of digital technologies in addressing the Grand Challenges~~

~~Several things are clear from the “Grand Challenges” paper and other discussions of the future direction for wind energy. Firstly,~~ the challenges cover multiple scales in space and time. ~~Secondly~~Third, they are interrelated and cannot easily be separated~~. And, thirdly,~~ , and thus addressing them will need an interdisciplinary ~~research and development approach.~~

~~These three points suggest the need to combine and use data from many different sources and disciplines. Accordingly,~~ R&D approach. These points suggest in turn that combining, using, and sharing multiscale and interdisciplinary data will ~~play a fundamental role in addressing each of the wind energy Grand Challenges, fuelling~~ be an essential, cross-cutting capability to enable the transition to a renewable energy system. ~~The opportunities are potentially considerable ; as a~~

Other industries have already recognised the considerable potential for the opportunities for the use of data; as the authors of the U.S. Chamber of Commerce Foundation research report *The Future of Data-Driven Innovation* noted in 2014,

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[1] ~~See https://science.sciencemag.org/content/366/6464/eaau2027/tab-e-letters.~~

> “Regardless of what form it takes, data tells a story. It can identify cost savings and efficiencies, new connections and opportunities, and an improved understanding of the past to shape a better future. It also provides the details necessary to allow us to make more informed decisions about the next step we want to take.” (?)

~~In this paper, we explore the possibilities offered to the wind energy sector by the availability of continuously developing digital technologies—such as storage, connectivity, computational power, data management, data science tools, digital twins, and many others—to exploit the ever-increasing amount of data. These lead to opportunities for efficiency , innovation, and entrepreneurialism. Together, these are many of the essential aspects of~~

1.2 Using data to enable the green energy transition

The effective use of data is foreseen as a lever for the global green transition through empowering information and communication technologies to increase resource efficiency and to accelerate research and development (??). We consider the effective use of data to be a key characteristic and outcome of digitalisation, which we define as the organisational and ~~industry-wide~~ sector-wide use of data and digital technologies to improve efficiency, create insights, and develop products and services. ~~In short, digitalisation is doing new, value-driven things with data and tools generated in digital form by the digitisationprocess.~~

~~Digitalisation is foreseen as a lever for the global green transition through empowering information and communication technologies to increase resource efficiency and to accelerate research and development (??). This process is already happening in many sectors~~ Digitalisation should not be confused with digitisation, which is the conversion of information into digital forms, and thus one of several precursors to digitalisation.

This use of data is increasing in other sectors as well; the manufacturing sector has seen that significant business advantages can be obtained by combining automation and data exchange with manufacturing technologies, which is itself a form of digitalisation. This trend is known as “Industry 4.0” and follows previous sector-wide manufacturing industry transitions including the use of steam power, electrification, and the introduction of computing. There are reasons to expect similar trends in energy; in 2017, a report by the United Nations Industrial Development Organization (UNIDO) noted

> “The sustainable energy transition and Industry 4.0 share important characteristics: both are highly influenced by technological innovations, dependent on the development of new suitable infrastructures and regulations as well as are potential enablers for new business models.” (?).

Historically, ~~such technological transitions~~ technological transitions like the renewable energy transition and digitalisation are driven by a combination of curiosity, need, and cultural pressures, and occur when a disruptive technological innovation emerges from a niche (?). Strong connections between the niches and the broader landscape help to create a pull for new technologies that are relevant to users, helping increase adoption. Often the process of adoption is transformational for both the new technology and the market, and while some new innovations fail, others go on to become part of the technological landscape. The process of innovation therefore does not happen at the same time across a sector, but is instead uneven and happens opportunistically, and probably where the barriers are lowest. The more barriers can be removed or lowered, the higher the potential for innovation.

1.3 ~~Opportunities for the use of data~~

~~Data has many applications in the~~ This paper discusses how the digitalisation of the wind energy industry ~~and is already helping to improve efficiency and create new business models. For example:~~ could support the renewable energy transition, the barriers that exist to digitalisation, and how the wind energy industry itself must adapt to enable digitalisation. We explore the possibilities offered to the wind energy sector by the availability of continuously developing digital technologies—such as storage, connectivity, computational power, data management, data science tools, digital twins, and many others—to exploit the ever-increasing amount of data. These lead to opportunities for efficiency, innovation, and entrepreneurialism. Together, these are many of the essential aspects of digitalisation. Businesses, organisations, industry sectors and societies undergo a digital transformation when they adopt digitalisation on a large scale, while digital businesses are those that are largely based on digital products and services. To help understand and differentiate between these similar terms we provide an overview in Table **??**.

Table 1. Definitions for digitisation, digitalisation, digital transformation, and digital businesses

Digitisation	the process of converting information into digital signals, enabling digitalisation (**?**)
Digitalisation	the organisational and industry-wide use of data and digital technologies to improve efficiency, create insights, and develop products and services
Digital transformation	the holistic process which integrates and adopts digitalisation on societal levels (**?**)
Digital businesses	businesses that incorporate digitalisation into their activities and derive a significant part of their turnover from digital products and services

1.3 Scope of this paper

Our goal in this paper is to identify sector-level Grand Challenges in the digitalisation of wind energy. We consider these Grand Challenges to be things (1) that must be done for the wind energy sector to digitalise; (2) that impact many different stakeholders; and (3) require coordinated effort to solve. They might also be issues that are seen again and again in different markets, such that they are the same challenge but with different solutions. Identifying the Grand Challenges for digitalisation therefore requires combining an understanding of the process of digital transformation with many different stakeholder perspectives.

An initial literature review revealed that there is extensive research and development (R&D) taking place within the wind energy community along many avenues (see e.g. **?**, for an overview). This R&D often leads to the creation of algorithms or software that could have application in industry or form the basis of digital businesses. And, there are many transferable digitalisation technologies available as part of the Industry 4.0 transition. But, we also found that few studies have examined the consequences, level, and trends of digitalisation in the wind energy industry. In response to this apparent lack of research, we report here the results of a literature survey and data collection activities to understand how digitalisation is progressing, how it might lead to fundamental changes in the wind energy industry, and the issues that would be faced *en route*. Understanding these issues is crucial for identifying the Grand Challenges.

We identified three Grand Challenges in the digitalisation of wind energy. These are related to data, culture, and coopetition. They include (1) the need to create a framework of Findable, Accessible, Interoperable and (Re) usable (FAIR) data data; (2) the need to connect people to that data to foster innovation; and (3) the need to enable collaboration and competition between organisations.

This paper is targeted at policy advisers, funding agencies, research managers, and others involved with technology transfer at a strategic level. We expect that it will also be of interest to technologists and researchers as it may provide insight into future research directions.

The next section provides a short introduction to the opportunities presented by the digitalisation of wind energy. Section **??** presents the results of an initial expert elicitation that informed this study and the identification of the Grand Challenges. Section **??** describes the process of digital transformation in the context of wind energy. Section **??** provides lessons learned from other high technology networked industries. Based on this, we carry out a more specific expert interview series and use the results to identify the Grand Challenges for the digitalisation of wind energy in Section **??**. Section **??** presents our conclusions.

2 Using data to reduce the cost of energy from wind

The financial performance of a wind energy facility can be summarized using the levelized cost of energy (LCOE). This is the average cost to produce a unit of electrical energy over the lifespan of a wind plant. There has been a strong drive to reduce LCOE over recent years (**?**), resulting in wind energy often being the cheapest new source of energy in many markets (**?**). This trend is expected to continue (**?**), which is essential if wind energy is to remain a significant source of energy in future.

LCOE is driven by several factors including CAPEX and OPEX, the cost of project financing, and the income from energy sales. Data can be used in many different ways to reduce the LCOE of a wind energy plant:

- ~~Data about a wind energy development site's characteristics are fundamental requirements for many different aspects of site design and optimisation (see e.g., **???**). Experience from operating sites is used to calibrate and refine the design process and improve new sites.~~ **CAPEX** is the capital cost of the wind turbines and foundations or substructures of a wind farm. Access to better site information, more accurate wind turbine models, and better wind farm simulation tools as a result of digitalisation therefore allows wind turbine and wind plant designs to be better adapted to the likely operating conditions, potentially saving on raw materials or increasing reliability. Similarly, digitalisation makes it easier to use data from existing plants to validate design tools and the design process.

- ~~Large amounts of data are collected on wind turbines by sensors installed by the original equipment manufacturer (OEM). Coupling sensor data with models of the turbine allows the creation of "digital twins" of wind turbines (**?**). These software representations of hardware are now available as commercial services and are frequently used for tracking~~

~~turbine fatigue loading and remaining lifetimes (?). Research is ongoing on ways to use this data to make intelligent control decisions (?). Similarly, data-based condition monitoring of wind turbines is common, with many companies using statistical analysis or machine learning to provide early warning of component failure (?). Third-party sensors are also gradually being used on wind turbines; for example, data from forward-looking wind lidar are used to inform control decisions such as blade angles or generator torque, potentially reducing loads (?).~~ **OPEX** includes both operational and maintenance expenses.

Operational costs arise through business management and technical management of the plant; data and digitalisation could help reduce these costs through improved (and cheaper) condition monitoring. Predictive maintenance based on data from condition monitoring systems can avoid unplanned maintenance, which reduces OPEX and increases energy production. These were high priority applications in a 2020 survey reported in **?**.

Maintenance costs can be reduced by minimizing the need for maintenance, and by reducing the business impact and cost of those actions. Wear and tear - which incurs maintenance - can be reduced by improved turbine design, and by minimising loads through controls that use turbine sensors (**?**) or integrate external information from e.g. wind lidar (**?**). Digital twins driven by sensor data can be used to quantify remaining lifetime and inform control actions or maintenance decisions (**???**). Maintenance can also be made easier or more effective through the use of virtual reality (VR) for maintenance planning, augmented reality (AR) to help technicians identify equipment, online manuals accessed using speech-recognition systems, inspection by unmanned aerial vehicles (UAVs) or the use of robots to carry out repairs, and many other tools (see e.g., **??**).

- ~~Wind energy needs to be integrated into our electrical supply. This means that wind turbines must respond to the grid at timescales on the order of seconds or less. Traditional thermally-powered electricity generators automatically change their power output in response to changes in grid frequency. Wind turbines lack this response. Instead, their output can be regulated by an external control signal or by monitoring the grid locally (?). Power forecasts driven by real-time observations also help enable the integration of wind turbines (?).~~ **Amount of energy** Digitalisation can increase the amount of energy generated by a turbine by detecting losses due to blade soiling, icing, damage, or erosion and allowing the operator to clean the blades, start deicing systems, or carry out repairs. It can enable wind-plant level control strategies that reduce wake interaction and thus reduce energy losses (**??**).

Access to wind data and market data – another aspect of digitalisation – can be used when planning regional and national transmission and distribution to help avoid supply shortages or curtailment (**?**), while automation can reduce curtailment compared to manual processes (**?**).

- ~~Available data is being used to understand the dynamics of wind fields as well as turbine reliability, evaluation, assessment, and performance (?).~~ **Value of energy** In some markets it may be possible to make more money from wind energy by selling it when market prices are high. Digitalisation can enable this by providing market simulations, through decision support tools for energy trading, or by informing energy storage strategies. Improved weather and demand forecasts – made possible by more data and digital technologies – are already being used by grid operators and energy suppliers to reduce imbalance charges and penalties, but the value of this depends on market structures (see e.g., **?**). Weather forecasts can also be improved by data sharing by multiple organisations in a region (**?**).

- ~~Existing processes such as wind resource assessment are gradually being encoded so they rely less on human inputs and thus run faster or more efficiently (**?**). This should reduce development times or allow optimisation, reducing the cost of energy.~~

- ~~Complex issues such as social acceptance and environmental impact are starting to be targeted (**?**). This has resulted in such ideas as using virtual or augmented reality to preview a wind farm before it is built or collecting real-time feedback from local residents about noise or flicker (**?**). Also, wind turbines can be linked with bird- or bat detectors to trigger avian-friendly operating modes (**?**); these may become even more important if such externalities are assigned a price in future.~~ **Financing costs** for a new wind plant are a function of many factors including the predicted uncertainty of energy production and the historical industry-wide accuracy of energy predictions. Reducing either uncertainty can reduce the cost of financing. This requires developers and their engineers to demonstrate the accuracy of their energy yield assessment processes, which can be done through internal or public benchmarking exercises whereby energy yield assessments are repeated for old development sites and compared against actual production data (**?**). Digitalisation enables this to be done more easily and faster within an organisation, or across a whole sector.

~~Digitalisation in the wind energy industry is progressing. But so far it tends to be vertical or siloed within an organisation or takes place directly between one organisation and another. This internal focus is not unique to the wind energy industry; Branca (2019) found that initial digitalisation efforts in the metals processing industry were often internal to an organisation and used to optimise internal processes, manufacturing, or products.~~ A future wind plant that benefits from digitalisation is visualised in Figure **??**. In this plant, many different organisations collaborated during the design phase to plan a facility that was optimised both for the operating conditions and grid conditions, reducing CAPEX and OPEX. Whilst in operation, the plant operator is able to make informed decisions about energy production and plant maintenance while accounting for market conditions and environmental or societal constraints. They can also share data and decisions across organisational boundaries with the many parties involved. This also reduces OPEX while maximising the income from energy production, increasing worker safety, and reducing environmental impact.

~~However, the wind energy industry is highly interconnected both physically and in terms of the interdisciplinary science and engineering that underpins it. This paper directly addresses the challenges in wind energy digitalisation, but additional technology, such as cybersecurity, are vital to enabling the future described. This, in combination with the innovation style of the leading industry actors (**?**), suggests that collaboration may be an important aspect of the future of digitalisation of wind. Steps have been taken to initiate collaboration, for example by sharing (some) research data through online platforms. By comparison, very little operational data is freely available, and the wind energy industry acknowledges its own reticence to share data (e.g., **?**).~~

2.1 ~~The potential for digitalisation to reduce the cost of energy~~

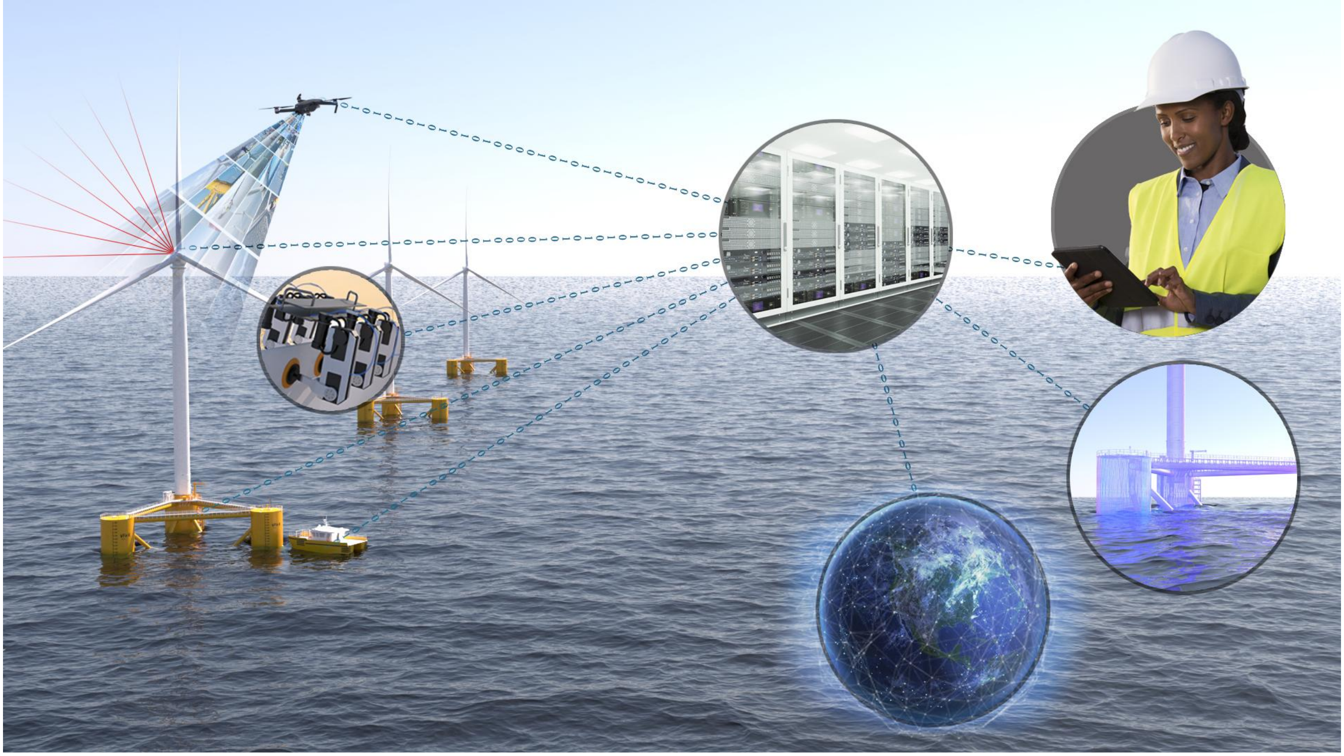

Figure 1. Digitalisation in action. In this future floating wind energy plant, digitalisation enables a plant manager to take data-based decisions in real-time, increasing safety and reducing the cost of energy. Image credit: NREL graphics team

The LCOE of wind energy can also be impacted through other related activities such as academic research, by developing ports and transport infrastructure, by advances in manufacturing, by workforce development, and other activities. Digitalisation in those areas could thus help reduce the LCOE of wind energy.

In researching this paper we found that it was very difficult to quantify the potential value of digitalisation and its contribution to LCOE. There are very few clear value statements available, and what statements exist, are hard to map from one use case to another as CAPEX, OPEX, and other terms in the LCOE equation are very wind-farm specific. Digitalisation is also an enabler of other services and thus its value is realised through those other services. One example of this is wake steering in operational wind farms, which requires data from across the wind farm to be collected, analysed, and acted upon. Recent analysis suggests its adoption could release an additional 0.5% to 2% in annual energy production (AEP) in US wind farms (**?**).

~~Access to wind turbine data can be leveraged to improve the wind turbine and wind plant design process, resulting in smaller uncertainties in loads, lifetimes, and power production. In turn, this saves on raw materials, saves on project financing costs, and increases stakeholder confidence. Studies estimate that this might allow a 1% capital expenditure (CAPEX) saving. As a large floating wind farm may be a multibillion-dollar investment (**?**), this could reduce CAPEX by tens of millions of dollars.~~

[1] ~~Without cultural changes that allow access to past data and technical changes that enable new approaches to designing and operating wind turbines, this saving would simply not be possible.~~

~~Operational expenses (OPEX) can also be reduced by coupling condition monitoring with intelligent maintenance scheduling, rather than simply responding to failures as they happen, potentially saving several percent of OPEX. One vendor of improved~~ Cost models have been developed for OPEX (?) that could be used to estimate the impact of certain digitalisation scenarios, but we lack the data to interpret these types of cost models across the entire wind energy industry. We note though that as whole, digitalisation will be one of the enabling factors for the expected continued reduction in LCOE through 2050, which **?** summarise as "across all wind applications, LCOE is anticipated to decline by 17–35% in 2035 and 37–49% in 2050 [relative to 2019]", with the majority of the reduction in LCOE (5-15%) due to improvements in CAPEX and turbine capacity factor, depending on whether the turbine is built on land or offshore. Reductions in OPEX were the third largest contributor to LCOE reductions by 2050, but might be possible to realise more immediately, rather than needing to design in to a new plant. And, they could have a significant impact on a wind turbine's (financial) performance. For example, one vendor of predictive maintenance using data and machine learning ~~estimates~~ claims that

> "~~. . . up to 30% of the levelised cost per kWh produced over the lifetime of a turbine can be attributed to Operation and Maintenance. . . "~~
>
> ~~They then claim that~~
>
> ~~"~~Using [brand name of a digital service], one can expect a reduction in replacement and labor costs. Assuming a 20% reduction in the repair and maintenance portion of O&M costs, this would translate into annual cost savings of $11,383 for a 2.5-MW turbine and $34,148 for a 7.5-MW turbine." [1] (**?**)

~~Scaled to a 100-turbine facility, this offers over $3 million~~ Over 25 years this offers approximately $285k to $854k in savings. But, ~~the assumption of 20% savingsmay be optimistic;~~ not all digital services achieve these savings: a wind energy industry market research company interviewed for this paper ~~, noted~~ noted that

> "... an average reduction of 11% of the operations and maintenance cost for operational assets when utilising predictive maintenance facilitated by data analytics versus conventional reactive maintenance practices."

~~In both cases, it is~~ It is also not clear how much ~~the digital~~ these services cost, so the net savings are unknown. ~~There are also some challenges to adopting predictive maintenance systems. One is the total cost. Reducing the life cycle costs of after-market sensors will likely make it easier to justify adding sensors to already-operating turbines, while the implementation of "plug-and-play" standardised virtual environments and the development of innovation marketplaces for data science applications will reduce the cost of providing services~~Without a clear understanding of the costs and benefits, adoption by customers will most likely be slow, sporadic, and limited (**??**).

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[1] ~~Estimated CAPEX for offshore wind energy systems in 2014 were around €3.5 - €4.5 Million per MW (?). A 1% CAPEX saving for a gigawatt-scale plant is therefore equivalent to €35 - €45 Million. Even with up to 50% reductions in future offshore wind CAPEX due to industry learning, this would be a valuable saving.~~

[1] ~~From "Maintenance 4.0 in wind farms: Bringing smart analytics to clean energy". https://industrial-ai.skf.com/maintenance-4-0-in-wind-farms. Accessed May 2021.~~

~~Digitalisation can also help increase the amount of energy delivered by a wind energy facility,~~ From the examples above it can also be seen that digitalisation in the wind energy sector is progressing, but tends to be vertical or siloed within an organisation or takes place directly between one organisation and another. Steps have been taken to initiate collaboration across organisational boundaries, for example by sharing (some) research data on online platforms but very little operational data is freely available, and ~~thus increase income. It can increase the efficiency of a turbine by detecting blade soiling, damage, or erosion; can enable wind-plant level control strategies that reduce wake interaction and reduce energy losses; and access to data can help when planning regional and national transmission and distribution to help avoid curtailment. A~~ the wind energy industry ~~market research company interviewed for this paper, noted~~

> ~~"The additional annual energy production (AEP) from selective power uprating has … resulted in approximately 2.4% additional power compared to the same average without the digital service being provided."~~

~~While significant, these values are below the double-digit gains promised by some digital service companies, and it is possible that over-selling has slowed the pace of industry~~ acknowledges its own difficulties in sharing data (e.g., **?**). This internal focus is not unusual during the adoption of ~~digital solutions~~digitalisation; **?** found that initial digitalisation efforts in the metals processing industry were often around optimising internal processes, manufacturing, or products, instead of across organisations' boundaries.

~~Additionally, digitalisation of wind energy potentially increases the value of the energy. Thisoften depends on market structure. One way to do this in open electricity markets is to store energy, and then sell it when it is more valuable. Automated energy trading or human-controlled energy trading with decision support tools is common in some markets but requires accessible data and an open exchange. Improved weather and demand forecasts are already being used to reduce imbalance charges and penalties, but this also requires specific market structures. Weather forecasts can be improved by data sharing by multiple organisations in a region~~The wind energy industry is highly interconnected both physically and in terms of the interdisciplinary science and engineering that underpins it. This, in combination with the innovation style of the leading industry actors (**?**), suggests that collaboration may become a more important aspect of the digitalisation of wind energy in future. Advances in other collaboration-related technologies such as communications and cybersecurity are therefore likely to be vital to enabling digitalisation in the wind sector, but this ~~approach will need secure data sharing to be effective.~~ need is not unique to the wind energy sector.

~~These examples are technology-focused cases of digitalisation, yet one must differentiate between digitalisation and a) digitisation, which is the conversion of analogue data and thereby the enabler of digitalisation (**?**), and b) digital transformation being the definition of the holistic process which integrates and adopts digitalisation on societal levels (**?**). The formal definitions used in this paper are given in Table **??**.~~

~~Definitions for digitisation, digitalisation, digital transformation, and digital businesses Digitisation the process of converting information into digital signals, enabling digitalisation (**?**) Digitalisation the organisational and industry-wide use of data and digital technologies to improve efficiency, create insights, and develop products and services Digital transformation the holistic process which integrates and adopts digitalisation on societal levels (**?**) Digital businesses businesses that incorporate digitalisation into their activities and derive a significant part of their turnover from digital products and services~~

~~These examples~~ These examples also show that the barriers to new business models are often not scientific or technical—because the underlying technologies generally already exist—but might be related to reluctance to share data, concerns around competition, are driven by commercial interest, or are related to the market they operate in. And, if the return on investment is unclear, the decision to initiate a digital transformation within an organisation might be deferred until more information is available.

The examples also introduce some of the important stakeholders in the digitalisation of a commercial wind energy facility~~.~~ ~~They~~ , which include investors, project managers, technologists, site workers, and many others. Research projects may have different stakeholders, ~~for example,~~ such as researchers and funding agencies. Each stakeholder group has ~~different~~ their own perspectives, which ~~further demonstrates how~~ raises the possibility that digitalisation is potentially as much a cultural challenge as it is a technical challenge.

2.1 ~~How digitalisation might affect how we work~~

~~To help the reader understand how digitalisation could impact the daily life of someone in the wind energy industry, we have combined some of the current technology and business trends - digital twins, predictive maintenance, drones, expert systems, and many others - into a snapshot of a few hours in the life of a colleague in the year 2030. While this is speculative, it helps see some of the impacts, opportunities, and challenges that digitalisation could bring.~~

~~Alice was involved in the initial engineering design of an 800-MW floating offshore wind plant that was built in the mid-2020s. She led the commissioning and has been managing it ever since. She has a simple remit from the project owners: to keep everyone safe and make sure that the plant meets its financial targets. Her story follows.~~

~~Alice's phone pinged, and her screen flashed with a warning: one of the new 20-MW floaters wasn't happy. They'd had a few teething problems with the power-to-fuel plant in one of the spars since they'd installed them off the coast a few years ago.~~

~~The plant was run by an intelligent supervisory system trained on data from an onshore pilot plant. It ran just fine most of the time, and maintenance requests were added to the site engineer's dockets automatically, but sometimes a human touch was still needed. Alice's screen greeted her with a few pop-ups each morning. Receiving those simple summaries of what had happened and why, and what could be done, really helped. All she had to do was tap a few buttons and move on to the next thing on her agenda.~~

~~Now that they trusted the automated monitoring, the maintenance folks had added automatic inspection and repair drone deployment to take advantage of good weather. Digital twins kept track of what was going on, and they were so accurate in predicting maintenance needs that some of the crew jokingly called them Digital Clairvoyants.~~

~~A few old-timers had grumbled when the system came online. They'd worried about being put out of a job by machines. Instead, they were now able to work on complex jobs where a drone or robot crawler couldn't go or couldn't figure out what to do. Now they could focus on the challenging jobs instead of taking on every job. This change also gave them the breathing room to focus even more on safety. And, as more plants came online up and down the coast and started sharing their weather data, the forecasts were improving too—no more getting caught out in high seas or freezing rain anymore.~~

~~The design team had seen it coming. Back in 2022, when the first prototype floating systems were commissioned, they'd invested in lots of sensors and engineering models for everything from the sea state to loads and fatigue. They let the world know that data was there and asked for help analysing it. The data and services marketplace that had grown was now benefiting everyone. Better-designed turbines and more reliable energy were reducing costs across the board. In contrast, some of their competitors had foregone installing sensors to save a few dollars. But now they had no idea what had caused some of the problems they had seen, or why their turbines weren't performing as expected.~~

~~Alice and her group, on the other hand, could leverage their treasure trove of data to understand what their turbines were experiencing and what the turbines needed. That data let them collaborate and innovate. And now, unlike their competition, they were seeing big savings - tens of millions of dollars at their site alone. They had larger turbines than anyone else, but cheaper and lighter. And the turbines were smart too, providing grid support services and not just pushing electricity to the grid.~~

~~The turbines could also power synthetic fuel production when the grid had more electricity than it needed. Now, the model estimates were telling them that they had sold more synthetic fuel futures to the local shipping lines than they were going to have available to supply in the next month. The updated model was only adjusted 5% from the original model a month ago, but the adjustment from the updated sensor information would earn them millions of dollars more over the years. With a wave of a hand, she sold back a future with a secure transaction on the open exchange to an unknown counterparty to banish the warning.~~

~~Although Alice's experience the operations phase of the plant, digitalisation will benefit all stages of the wind plant life cycle, from the design phase through construction and commissioning, to operations and maintenance (Figure **??**). And these are not fiction or wishful thinking; many of the opportunities seen in the story have already been demonstrated and are approaching commercialisation or are already in daily use.~~

~~Digitalisation in action. In this future floating wind energy plant, digitalisation enables a plant manager to take data-based decisions in real-time, increasing safety and reducing the cost of energy. Image credit: NREL graphics team~~

2.1 ~~A research-driven assessment of the Grand Challenges for digitalisation~~

~~An initial literature review revealed that few studies have examined the consequences, level, and trends of digitalisation in the wind energy industry. In response to this apparent lack of research, we report here the results of a literature survey and data collection activities to understand how digitalisation is progressing, how it might lead to fundamental changes in the wind energy industry, and the issues that would be faced *en route*. Our goal is to identify sector-level Grand Challenges for the digitalisation of wind energy. We consider these to be things that must be done for the wind energy sector to digitalise; that impact many different stakeholders; and require coordinated effort to solve. They might also be issues that are seen again and again in different markets, such that they are the same challenge but with different solutions. Identifying the Grand Challenges therefore requires combining an understanding of the process of digital transformation with many different stakeholder perspectives.~~

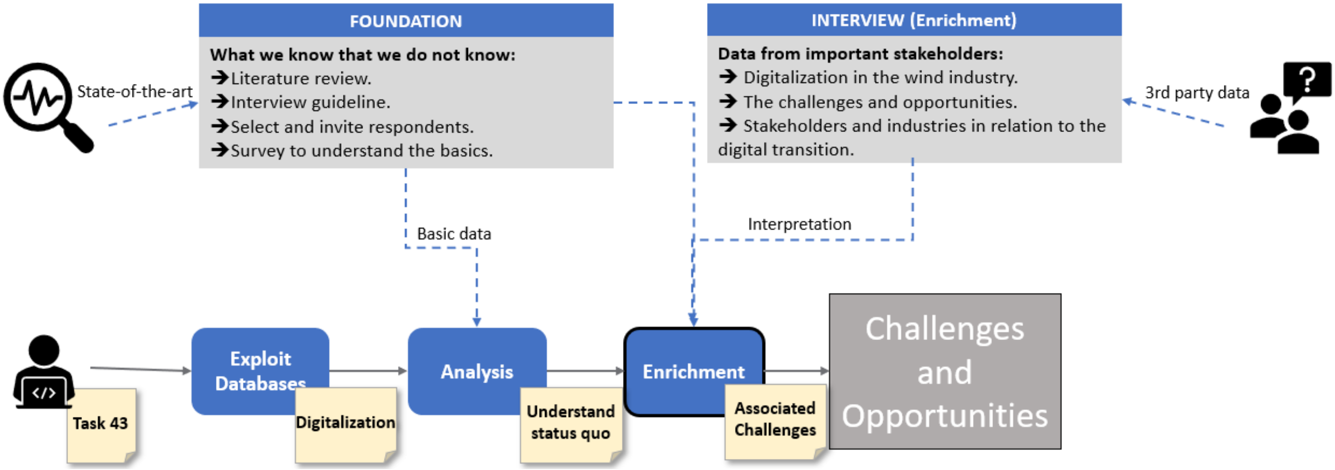


Figure 2. ~~Data~~ Flowchart showing how data collection, processing, and analysis were used to help identify the Grand Challenges~~for digitalisation of wind energy~~

~~This paper is targeted at policy advisers, funding agencies, research managers, and others involved with technology transfer at a strategic level. We expect that it will also be of interest to technologists and researchers as it may provide insight into future research directions.~~

~~Section **??** presents the results of an initial expert elicitation that informed this study and the identification of the Grand Challenges. Section **??** describes the process of digital transformation in the context of wind energy. Section **??** provides lessons learned from other high technology networked industries. Based on this, we carry out a more specific expert interview series and use the results to identify the Grand Challenges for the digitalisation of wind energy in Section **??**. Section **??** presents our conclusions.~~

3 Research Methods and Materials

The Grand Challenges in the science of wind energy were identified through a process of expert ~~elicitations~~ elicitation and synthesis (**??**). In this paper, we follow a similar process~~(Figure **??**)~~, shown in Figure **??**. First, a literature survey coupled with expert elicitations were used to understand the current state of digitalisation in the wind energy sector and actors' perceived challenges. We then refined some of this information through further interviews. The results of the ~~literature survey~~ expert elicitation are presented in this section, while the results of the literature survey are presented in context in Section **??** and Section **??**. This information is combined in Section ~~**??**~~ **??** to identify the Grand Challenges in the digitalisation of wind energy.

3.1 Data collection

The data presented and applied in this study relies on an empirical collection via a survey and semi-structured interviews with digitalisation experts, innovation frontrunners, and energy industry market leaders. Other community surveys have also been carried out recently, and their published results have been considered when preparing this document. For example, in 2019, a survey was carried out to explore the expectations and priorities of wind energy operations and maintenance experts (**?**). The data collection and subsequent processing and analysis followed the process exemplified in Figure **??**.

3.2 Survey

Members of International Energy Agency (IEA) Wind Task 43 and the wind energy industry were surveyed to determine trends of digitalisation in wind energy. The 102 respondents provided 68 different open answers to four questions, which were analysed and used as background knowledge in this study. A specific emphasis was targeted towards critical trends where data management and data sharing were found to be the most critical trends in digitalisation today, while smart energy and robotics were listed as the topics of the future. The output is interesting, as respondents decided to focus on the prerequisite of digital activities as the critical trend of today, before diving into actual digitalisation activities.

3.3 Expert interviews

In parallel to the survey, semi-structured interviews were conducted with 44 digitalisation experts, mainly from the wind energy sector. The respondents were not involved in the initial survey. The interviews followed a guideline based on the initial literature review and IEA Wind Task 43's activities. They were organised to gather insights from a broad range of wind energy life cycle area experts and digitalisation technology area experts. The Task 43 team interviewed experts in many wind energy life cycle areas, including turbine design and manufacturing, development, construction, operations and maintenance, as well as life assessment and decommissioning. Several technology area experts in data collection, data management, data analytics, and automation were also interviewed (Figure **??**).

Beyond providing a general understanding of digitalisation efforts in the wind energy sector, we categorised the output of the interviews into separate challenges (Figure **??**) and opportunities (Figure **??**).

Figure **??** indicates that companies perceive data accessibility and knowledge sharing as greater challenges than culture and change management, when compared to research organisations. Nevertheless, consensus was established among the two stakeholder groups on the three dominant challenges.

Figure **??** highlights that the two stakeholder groups also consider data accessibility an opportunity. Model development and "communication and open source" were also considered opportunities; research organisations see the greatest potential in the latter.

The interview outputs were analysed and divided into industry and research-focused stakeholder groups, which again were represented by eight companies and five research institutions. Table **??** explains the top challenges and opportunities.

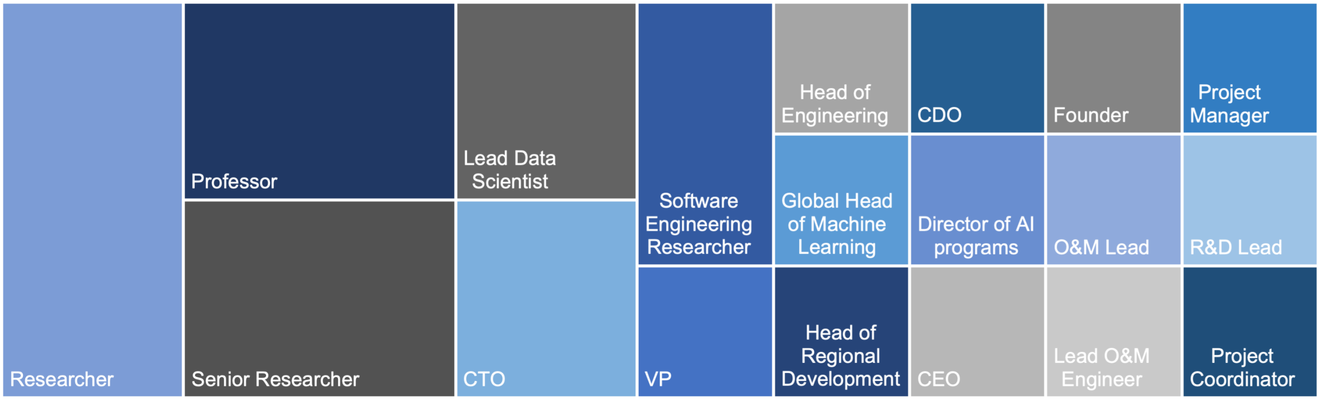


Figure 3. The interviewees' job titles. IEA Wind Task 43 interviewed 44 experts about wind energy digitalisation to help identify the ~~grand challenges~~Grand Challenges. The experts come from across the wind energy industry and have a wide range of roles, as evidenced by the many different job titles that they use. The size of the blocks shows the relative frequency of each title. Colors are arbitrary.

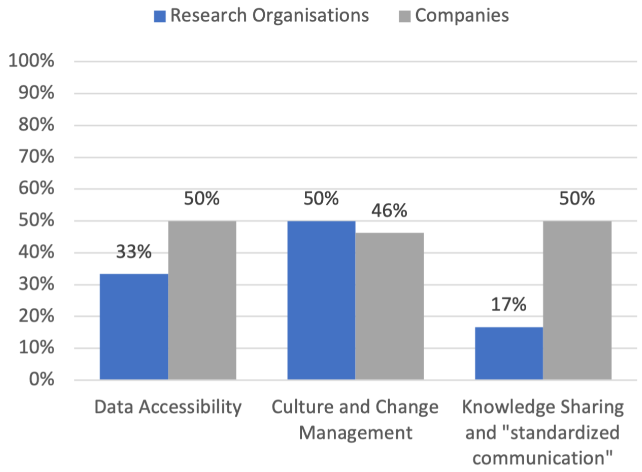


Figure 4. The top three digitalisation challenges in the wind energy sector mentioned during the interviews. The result is presented and analysed by stakeholders in academia, including research organisations, and in the private sector, respectively.

The identified challenges will be analysed following a retroductive approach in the following sections where the requirements, process, and opportunities related to the digital transformation of the wind energy industry will be discussed based on the output from the survey and interviews. Then, the outlook on digital opportunities will be analysed in relation to the digitalisation experienced in other industries. The empirical data collection, literature review, and analyses then identify the Grand Challenges in the digitalisation of the wind industry.

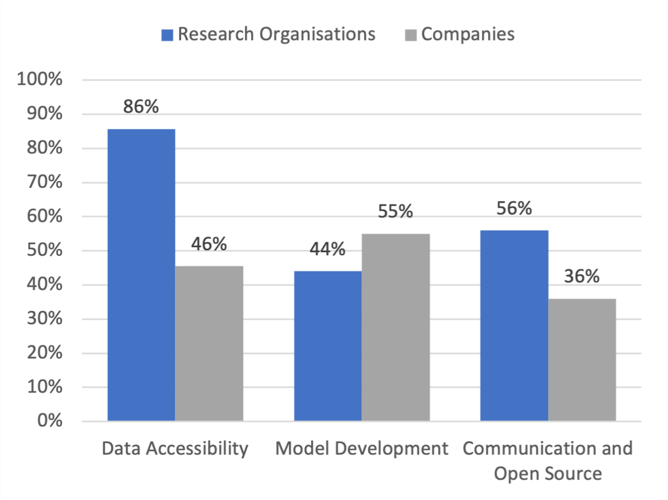


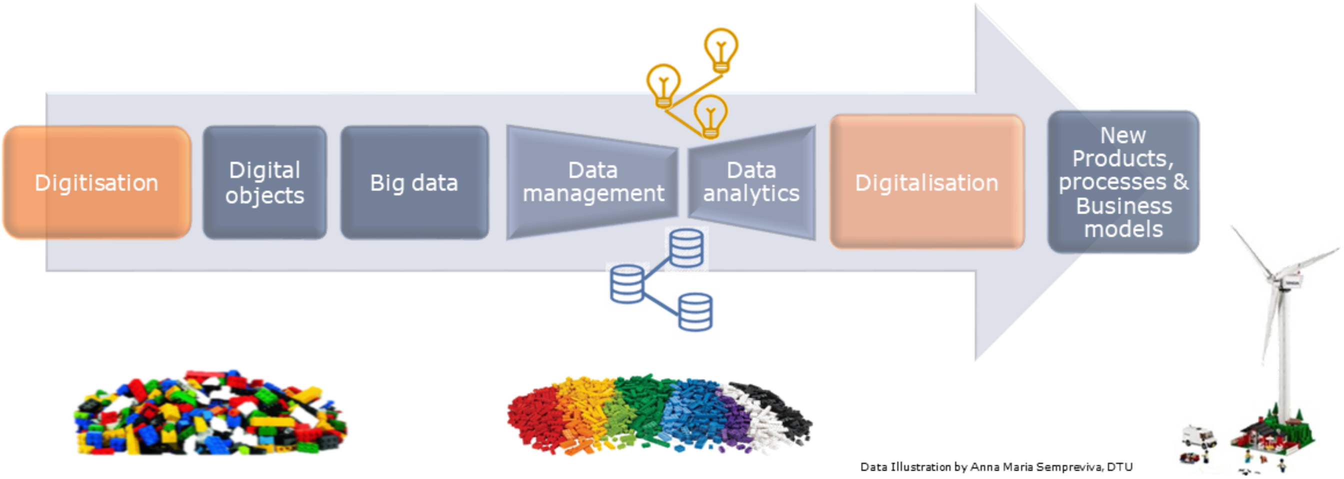
Figure 5. The top three digitalisation opportunities in the wind energy sector mentioned during the interviews for different types of organisations

Table 2. The top challenges and opportunities identified through the first interview series

Challenge or opportunity	Explanation
Culture and Change Management	The challenges associated with the digital transformation requires company alignment, personal motivation, coordination of the organisation with its people, and tangible use cases and outcomes.
Data Accessibility	The challenge addresses both the lack of data accessibility and sharing in the vertical and horizontal value chain, as well as the opportunity of obtaining more, and better quality, data than in the past.
Knowledge Sharing	The challenge of standardised structures for interorganisational sharing of models, best practices, collaboration beyond data, etc.
Model and Algorithm Development	The opportunity to describe phenomena and replicate such methods applied.
Communication and Open Source	The opportunity of open-source data, codes, and models, which simultaneously enables common communication and resource sharing among organisations.

4 Understanding the Digital Transformation

The survey data and interview findings described in the previous sections led us to further investigate the meaning of ~~the~~ a digital transformation. ~~This work provided us with a~~ Establishing what is meant by a digital transformation provides a framework for how ~~the digitalisation process generates the innovation that drives the digital technological transition. This transition occurs by~~ digitalisation can unfold, both making use of and taking advantage of ~~the availability of~~ digitised data and novel data science tools~~, thus leading~~. This transition leads to new products, processes, and business models (Figure **??**), ~~and~~ transforming the technological landscape.



Data Illustration by Anna Maria Sempreviva, DTU

Figure 6. Digital transformation is a process that goes from digitisation to digitalisation. After **?**

In this section, we consider each of the components of the digital transformation. We describe some of the benefits and challenges associated with each of them and where we see a bottleneck in the process. Finally, we summarise the key aspects of the digital transformation most relevant for the wind energy industry, which are used towards defining the Grand Challenges in Section ~~??~~??.

4.1 Digitisation: converting information from analog to digital

Digitisation is the process of converting information into digital signals (**?**)~~, which fuels the digitalisation process. Digitisation can take many forms. One common example is the digitisation of sensor signals from infrastructure throughout the wind energy system. Other examples include construction and maintenance records. And, processes - such as maintenance scheduling - and algorithms - such as energy trading decisions - can also be digitised so that they can be captured in software. This may also mean formalising processes, although it may be more sustainable and flexible to break longer processes into modules that can then be combined as required.~~. The aim of digitisation is to provide the raw material for later use in digital business, and so it is important to capture as much information as possible in digital formats. Examples of digitisation in the wind energy industry include:

- Converting analog sensor signals from turbines or infrastructure into digital form
- Converting written records such as maintenance logbooks into digital records
- Formalising decision making processes as algorithms and recording how individual decisions are made
- Capturing business processes in software

Sensor information from hardware in the wind energy system will be fundamental for releasing the opportunities of digitalisation. Wind turbines and other hardware in the wind energy system are extensively instrumented, and the data are brought together in data systems (often known as Supervisory Control and Data Acquisition systems or SCADA systems). This simplifies the process of data access. However, ~~as we noted in our scenario,~~ turbines are usually only instrumented with the sensors ~~needed~~ necessary to support the manufacturer's and operators' ~~needs~~goals, which might be less than are required for ~~some~~ other applications. This helps reduce costs of manufacturing and sensor maintenance. Also, although extensive data buses are in place at most wind farms to connect wind turbines and the plant controller, security limitations often mean that it is impossible to connect other sensors to these networks, and that it might only be possible to access sensor data through the turbine's own SCADA system.

The lack of access to turbine data limits the development of software-based third-party solutions, while the lack of data connections means that third-party solution providers often have to develop both the sensor and the data transmission tools, further raising costs. To avoid a situation in which multiple entirely new networks are built on top of each other in future wind farms, it would be helpful for wind farm developers and their engineers to plan in a high-bandwidth open network on new wind farms, with strong security implemented at the hardware level (**?**).

Even with access to SCADA data, challenges remain in extracting information from the data. SCADA data semantics are particularly complex, and it may be necessary to develop an ontology (§**??**) in order to understand data from each different turbine model. This ontology could in turn be leveraged to form a schema to enable data exchange.

For all that wind energy uses wind for its fuel, there is a relative lack of information about the wind fields in and around wind farms. This may change through the deployment of remote sensing by lidar, sodar, and radar, or mobile *in situ* sensing by drones (Figure **??**). The extra costs of such devices will have to be ~~justified by~~ balanced by cost savings such as reduced turbine fatigue, or increased income in flexible energy markets where an operator can make an informed cost-benefit decision. As ~~wind lidars~~ remote sensing and mobile sensors have not yet become standard equipment on wind turbines or at wind farms, there is evidently still work to be done to justify their integration.

~~Digitisation costs money. Therefore,~~ The wind energy sector is transitioning to digital, but the process is far from complete. The digitization of data, knowledge, and tools is producing big data in the sector. However, creating the right environment for innovation requires further digital technologies. Wind energy requires information science to keep datasets retrievable by agreeing on and creating sets of general and domain-specific metadata (i.e. information about data) with related controlled vocabularies. Additionally, it needs data engineering to create and implement digital infrastructures for storing and analyzing data, as well as creating and connecting infrastructures for data and governance to regulate data sharing and collaboration to deal with sensitive and proprietary data. All of the above actions in turn require money and time to convince stakeholders of the value of the investment in digital technologies; without a clear business case or plan for using ~~digitised~~ digitized data as part of ~~a process of digitalisation , there may be a perception that digitisation is expensive , along with some resistanceto starting the process. Although—as in Alice's case—some companies may choose to gamble that later investigators will be able to monetise data, others will require a cost-benefit analysis.~~ the digitalisation process, the perception may be that the process is expensive and it might be met with resistance. While researchers have ~~been able to show~~ shown potential benefits from ~~digitisation and subsequent digitalisation, for example, by~~ digitalisation, such as reducing fatigue loads or ~~reducing~~ actuator use, they ~~are often unable to~~ often cannot convert these into meaningful fiscal benefits~~; in this example, collaboration is required between turbine~~

~~OEMs and plant operators~~. This step will require further collaboration between the research community, wind turbine OEMs, plant operators and others to develop baseline cost models that could be used for such studies. ~~Other factors can contribute to a reluctance to digitise, for example, the cost of storing data, the difficulty of creating metadata (i.e., information about the data), or the need to develop new processes to deal with sensitive data. However, without digitisation, digitalisation cannot start.~~

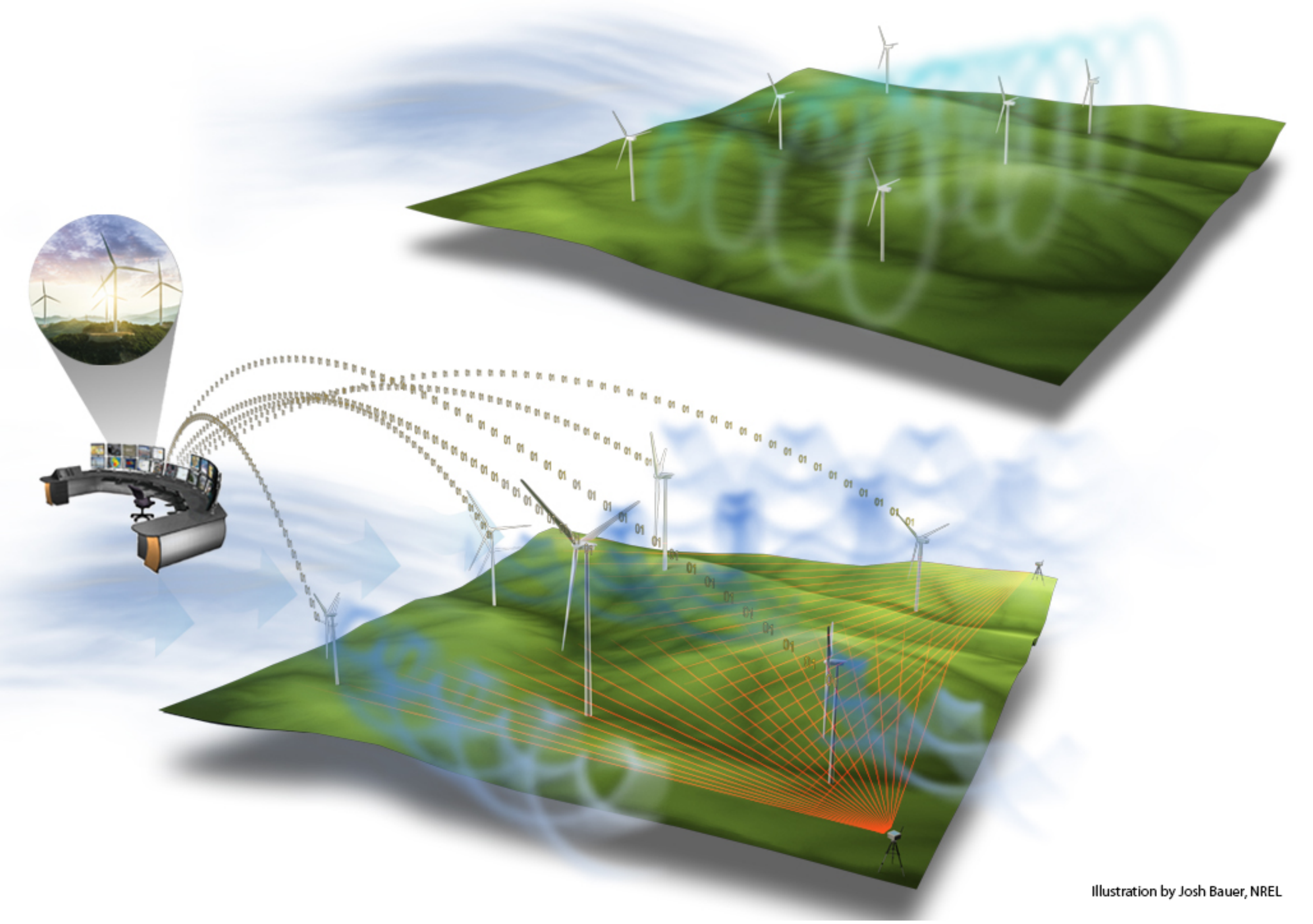


Illustration by Josh Bauer, NREL

Figure 7. Combining data from sensors across all parts of the wind energy system will be key to transitioning from today's isolated assets (top) to the interconnected wind plant of the future (bottom). Illustration by Josh Bauer, NREL from NREL/TP-5000-68123 (**?**). Used with permission.

4.2 Digital objects

Digitalisation requires that people or machines can find ~~and make sense of~~ the data created ~~through~~ by digitisation, and then ~~act upon it. Data~~ and make sense of it. Digital data alone (i.e., raw binary records) become usable through the addition of human-and machine-readable metadata, that describe and package the data and place them in context, which turns data into discrete "digital objects" (**?**).

Digital objects can be created from many different data sources. As well as ~~the~~ turbine sensor readings~~that Alice was using~~, they might include research reports, software models or tools, algorithms, and many other things (Section **??**). But these digital objects alone cannot be used effectively as part of a process. Instead, they need to be made findable, accessible, interoperable, and reusable (FAIR; **?**):

- **Findable** means that data can be discovered by people or machines through a search engine. Data can be made findable by identifying the data through the addition of metadata (a list of terms) which follow a defined schema. The metadata can then be aggregated for a dataset, and users can search through it to find the specific data they require. The process of making data findable adds time and cost to the creation of data, but if data are not findable, they will never have the chance to generate value.
- Once the data has been made findable, it needs to be made **accessible**. This means that the data should be retrievable using secure but open and free protocols, for example through the internet.
- It is rare that one piece of data is sufficient. Therefore, data needs to be **interoperable** so that it can be used in a workflow or applications. In practice, this means the need for machine-readable data and relationships.
- To maximise the benefit of sharing data and digitising processes, data should be **reusable** so that they can be applied to different settings. Reusability by anyone besides the original creator requires that data be findable, accessible, and interoperable.

Making data FAIR enables their effective use as part of a process and makes it easier for a digital business to obtain and use the data they require, and is thus an important step in digitalisation. For example, the creation of digital objects makes it feasible to implement large "data lakes" of all kinds of data in multiple formats, instead of rigid warehouses or structured relational databases (**?**). In data lakes, digital objects can be added to the lake with appropriate metadata and then retrieved as required. Indexing services offer the potential to create distributed data lakes that cross organisational boundaries, for example for research data so that users can access data from an ad-hoc mix of sources (e.g. for the New European Wind Atlas **??**). The use of data lakes reduces the overhead required with maintaining a data structure, such as weather observations organised by year, month, and day. In some cases, the transition away from organised or structured data to data lakes can be challenging. It can be perceived as risky, as unstructured data can become hard for humans to find and relies instead on software to access data. Although this risk can be mitigated through software testing, user training, and other measures, the perception of this risk is one example of the nontechnical challenges that are faced in digitalisation.

~~There are a number of other challengesassociated with making data FAIR. These include agreeing upon~~ Making FAIR domain data involves a range of challenges, including (i) gaining agreement among large communities on a common metadata schema,~~deciding on common variable names and data structures, adoption of common metadata schema or data structures, providing incentives for making data accessible (e.g., through marketplace concepts) , and developing a common platform~~

~~to do this~~(ii) determining common terms for controlled vocabularies/taxonomies, incentivizing data accessibility, and (iii) developing infrastructures for storing, analyzing, and curating data. The European Commission ~~pushed~~ has supported the use of ~~the~~ FAIR principles by researchers through ~~several initiatives ; applicants for research funding were partly assessed~~ initiatives such as assessing research funding applicants on their plans ~~to provide open access to data and publications; and~~ for open data access and indirectly funding the development of sector-specific taxonomies~~that have made it easier to apply metadata and make data findable. An example is the prototype of the Sharewind metadata registry (**?**) created by the members of~~ . During the European FP7 Projects Integrated Research Programme on Wind Energy (IRPWind) IRPWind.eu, a metadata schema and related taxonomies for wind energy were created, resulting in the development of a proof-of-concept for a metadata management system and registry based on semantics (See section 4.3) (**?**). The goal of IRPwind was to promote collaboration, standardization, harmonization, and knowledge transfer within the project while ensuring that the data produced complied with FAIR principles. The involvement of major organizations in wind energy in Europe associated with the European Energy Research Alliance, Joint Programme on Wind Energy (EERA JP Wind~~Energy)partners in the European Seventh Framework Programme (FP7) Coordination Action project Integrated Research Programme on Wind Energy (IRPWind).~~), further ensured the quality of work done by expert elicitation, enabled dissemination and increased acceptance of the results. IRPWind helped advance the adoption of FAIR data principles in the wind energy sector (**??**).

FAIR data are an enabler of open science. Open science is the shift to collaborative scientific development based on transparent and accessible knowledge (**?**), which has recently gathered pace. Making data FAIR is a prerequisite for openness as it follows the principle that " data should be as open as possible, as closed as necessary" (the H2020 Program's Guidelines on FAIR Data, **?** .

The official adoption of open science for "Horizon Europe" projects in 2018 will ~~also~~ thus likely lead to more awareness and adoption of the FAIR principles. In addition, the United States Department of Energy issued a funding opportunity announcement (FOA) in 2020 for artificial intelligence frameworks (including data) that utilise the FAIR guidelines and principles:

> "The DOE SC program in Advanced Scientific Computing Research (ASCR) hereby announces its interest in making research data and artificial intelligence (AI) models findable, accessible, interoperable, and reusable (FAIR) to facilitate the development of new AI applications in SC's congressionally authorized mission space, which includes the advancement of AI research and development. In particular, ASCR is interested in supporting FAIR benchmark data for AI; and FAIR frameworks for relating data and AI models." (From FOA DE-FOA-0002306, **?**)

~~While the FAIR data principles are an enabler of open science – the shift to collaborative scientific development based on transparent and accessible knowledge (**?**) – FAIR data are not necessarily open data. Instead, FAIR data are a prerequisite for openness following the principle that " data should be as open as possible, as closed as necessary" according to the H2020 Program's Guidelines on FAIR Data (**?**).~~

4.3 Big data

Digitisation will change the characteristics of the data available to people and organisations. Data volumes increase—hence "big data"—the data are moving or changing at higher velocity, the data are only useful if they can be given value, the data come in many different varieties, and the veracity of the data needs to be checked and ensured. These challenges are known as the "five Vs" of big data for the volume, velocity, value, variety, and veracity of data (**?**). Practically, data becomes "big" when it cannot be handled using existing approaches. For example, when data volumes exceed storage capacities on a typical desktop computer, they require specialised storage and analysis tools. As a result, what is considered big data is not fixed, but changes depending on the user as storage gets cheaper, computing power increases, or new software is developed.

Although it brings challenges, such a level of data availability also brings advantages, for example the ability to aggregate information across a fleet of wind turbines, or to look at an entire wind plant project from first idea through to decommissioning. Furthermore, this ability to see the whole picture allows organisations to identify, explore, and act upon hidden relationships when appropriate data management and analytics tools are available.

Many tools have already been developed to help users deal with big data. One way to cope with big data is to store it together with metadata to enable its management. Cloud-based computing allows users to manipulate much larger amounts of data than can be processed on a desktop computer, while dedicated search tools allow the data to be queried. Similarly, visualisation can help understand big data (**?**).

Another challenge with big data is the need for organisational IT services that span physical infrastructure and cloud-based or remote infrastructure. This can bring pricing uncertainty and also increases an organisation's attack surface and can also require very specialised knowledge. An alternative is to devolve responsibility to individual users, but this can rapidly result in a patchwork of independent solutions.

Taking cues from the tech sector (e.g., LinkedIn, Google), we expect that metadata will be an increasingly important aspect of big data analytics. A database noting previously useful connections, verification studies, and framing a general knowledge map will likely assist in developing next-generation analysis approaches. For example, a knowledge map could assist a large owner in recognising and connecting maintenance data from a diversity of contractors. This is known as the "open-world" assumption, where it is not assumed that all data will be acquired in a standard form.

The issues and challenges of big data are generally well-known, and solutions exist. The next step in digitalisation is then to make data available to the right users to provide insight and apply outcomes. This requires effective data management and data analytics.

4.4 Data management: right data, right user, right time

A digital work flow setup for a problem solving process requires access to data, such as sensor data, data processing or simulation codes, or other types of digital information. Data management policies describe how those data are collected, stored, and preserved, as well as who can access what data. Data management is therefore required to get the right data to the right users within an organisation, and to manage data sharing across organisations. It is one of the steps for making data FAIR, as discussed in Section **??**.

Data management ~~also encompasses~~ is the enabler for data discovery and data sharing. Data discovery is the process of finding the appropriate data in a data storage. Although this can be done by querying the data directly, it is easier to search for data when they are tagged with the required metadata (**?**). Ideally, metadata would follow a standard schema so that all data can be queried at once. ~~Metadata can be made even more useful if the schema are populated using values~~ The schema would ideally be populated using terms from a controlled vocabulary (e.g., a sensor might measure a physical property that is one of "wind speed", "air temperature", or "air relative humidity"), rather than letting the user choose freely (**?**). This ~~reduces the number of terms that need to be used in searching for data. This~~ approach has been used in the recent IEA Wind Task 43 ~~Standardized Measurement~~ Wind Resource Assessment Data Model (**?**) ~~.~~as well as the IEA Wind Task 43 Glossary (**?**). The IRPWind project introduced in §**??** produced a metadata schema, and the design and demonstration of a metadata catalogue called ShareWind. The metadata schema includes the list of general Dublin Core metadata as well as wind energy domain-specific metadata, populated using terms from related controlled vocabularies and taxonomies.

These controlled vocabularies can have whatever structure is required. For example, they could just be a list of terms, or could have a hierarchical structure that also implicitly includes relations between terms; these are known as taxonomies. They could also include relationships between vocabularies which are known as ontologies. Describing data by tagging it using these ontologies creates so-called semantic data models~~which further~~, which enables data discovery. ~~The IRPWind registry prototype~~ Some examples include the ISO 81346 reference designation system for power plants (**?**, RDS-PP;) as well as the IRPWind registry prototype (was hosted at *Sharewind.eu*~~was one early use of a taxonomy in the wind energy community. This bottom-up effort to compile a metadata catalogue for wind energy was set up by members of the IRPWind project. *Sharewind.eu*~~ , but the website is no longer active) which catalogued data using a metadata schema and related taxonomies or even ontologies based on expert elicitation (**?**).

Different domains may have their own ontologies and thus use different approaches to naming a variable depending on historical reasons and the importance of the variable in each field. ~~For~~ As an example, the wind energy community might describe a physical property measured by a thermometer simply as "air temperature", while the meteorological community might tag the same data using the class "atmosphere" with a sequence of children (e.g., "dry bulb temperature" and "wet bulb temperature", etc.). Such varied classifications prevent the easy exchange of digital objects across domains. Avoiding this discrepancy across domains is difficult, but it can be mitigated by making equivalences between terms, making the ontologies public and visible, and leveraging existing ontologies rather than developing new ones.

Following data discovery, sharing data is required if the data is to be used in a productive way by the organisation. Sharing can take many forms, including sharing data within a single team in an organisation to work on a problem together; sharing the data with different teams or units within an organisation to benefit from different knowledge and capabilities of different teams; sharing the data with partner organisations to get the most out of the data; sharing the data with clients; sharing the data with specific researchers within a project to work on R&D projects together; or even sharing the data with the wider community in an open innovation process. Data sharing can be made easier by using common metadata schema across organisations, and by developing data portal(s) that can query metadata catalogues at multiple organisations.

Willingness to share data is often linked to its perceived commercial importance. Commercially sensitive data might only be shared with a small group and needs to be protected and will almost never be shared outside of an organisation; this is usually known as closed data. Some data might be made available to a small group outside the organisation, or more broadly but under specific licence conditions. These are known as shared data. Other data might be freely accessible to anyone without restrictions; this is open data. Note that open data data is distinct from FAIR data, and that closed data should still be made FAIR for access within an organization. There is an emergent need for a spectrum of open data licensing approaches especially for artificial intelligence and benchmarking applications (**??**)

Sharing data or making it openly available would be a change from today's protected data and would require a new mindset, which could be encouraged by providing examples of the benefits of data sharing and its safety. One potential approach to get the wind energy sector used to sharing is to map and link databases that are distributed within and over different organisations. Each organisation then compiles and exposes a metadata catalogue of the data available for sharing. Then, a web crawler harvests the metadata and updates a central catalogue that is searchable by the community members. This approach has been proposed by the EERA JPWind Community ~~with~~ using the data registry ~~ShareWind. This approach makes data discoverable~~Sharewind to compile a metadata catalogue; datasets are searchable and discoverable, but not directly accessible; ~~data are protected by the owners who~~ Data owners can register their data in a catalogue and tag it using terms from joint vocabularies. This allows data owners to maintain control over data access without having to transfer the data. The use of tags also allows for filtered searches that single out the most suitable dataset.

Overall, this solution improves the visibility and findability of state-of-the-art tools and data that can support the digitalisation process towards innovative solutions. Data is housed at the premises of the owners who are responsible for protecting the data and can then make it available to approved users. In 2021, the EU H2020 Coordination action project FarmConners ~~decided to build on the ShareWind data registry and set up a searchable metadata catalogue called~~ allocated funding to translate Sharewind.eu into a next generation, truly FAIR *Share-Wind.*~~*com*to make data truly FAIR. Share-Wind.com~~ ~~*is being populated*~~ *net catalogue* resource by adopting the *GO FAIR foundation* FAIRification principles: the most important is to make metadata understandable for both humans and machines by assigning Digital Object Identifiers (DOIs) to data and Persistent URL (PURLs) to standardized community metadata and controlled vocabularies. The ShareWind/Share-Wind prototype family has been tested by different communities including the New European Wind Atlas ~~NEWA~~(NEWA), FarmConners, and IEA Wind Task ~~41, and others.~~ 41.

Several other platforms exist to share ~~FAIR~~ wind energy data with the wider scientific community~~, for example~~. ~~*zenodo*~~*Zenodo.org* ~~, and~~ is an often-used platform where some wind energy-related communities have started to build up data collections on them. These platforms are not automatically FAIR as datasets can be tagged using owner-chosen keywords and some effort is often required to add FAIR domain metadata and controlled vocabularies/taxonomies.

The wind energy industry is also starting to make data available; the Danish energy company ~~Oersted~~ Ørsted has provided access to data from several sites since 2018, and in 2021, SGRE announced a data portal that can be used by industry and researchers. These few initiatives highlight (by comparison) that most energy-sector data is closed data and cannot be accessed. In 2022, IEA Wind Task 43 made a concerted effort of compiling a catalogue of 38 open data sources related to the wind energy sector (**?**).

A significant challenge to data sharing outside organisations comes from the need to agree on the terms of use for the data. This is usually done through licenses. But there are many potential licenses that can be chosen; as an example, ~~Zenodo~~ the zenodo.org data repository allows users to license data under one of ~~489~~ over 500 pre-existing licenses (**?**), or to add their own[1]. The need for data providers to choose a license and for data consumers to understand the license, costs time and requires specialist support. Licensing can therefore be expensive and slow, and so may act as a barrier to sharing by organisations. Some solutions to this challenge that are being worked on to the knowledge of the authors include:

- Digital Rights Management (DRM) solutions, which aim to control the use, modification, and distribution of copyrighted information.
- Data licensing, whereby asset owners and operators generate extra royalty income at no extra cost by providing data platform operators the opportunity to monetise the sales and market intelligence value of their data on their behalf, for example.
- Pre-emptive licensing has been used by The Open Energy initiative. Participants in the initiative were required to agree to a common license to be able to participate.
- Data leasing, in which access is granted to data through an API where all the data analysis scripts are monitored.
- Encrypted analysis, in which algorithms are delivered to the data rather than the other way round.
- Federated analytics and differential privacy machine learning techniques, where data is virtually aggregated, allowing organisations to anonymously pool their data. While these techniques offer great opportunity to bypass concerns around proprietary data sharing there can be a trade off between privacy and data accuracy which needs further exploration.

4.5 Data analytics

Data analytics is the processing of data to find insight. It includes inspecting, cleaning, transforming, and modelling data. Although data analytics have been used in the wind energy industry for some time, the increased amount of data resulting from digitisation, and the increase in computing power (following Moore's Law and through the availability of cloud computing) will give data analytics an opportunity to add ~~tremendous value and even~~ value and uncover new business models (see examples in Section **??**).

With the availability of more data, both historical and real time, models will be able to scale accordingly to be deployable in the real world. **?** highlights this difficulty in wind energy when explaining "A big challenge such organizations now face is the question of how the massive amount of operational data that are generated by large fleets are effectively managed and how

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[1] ~~The complete list of licenses available through Zenodo can be found at https://zenodo.org/api/licenses/?page=1&size=1000.~~

value is gained from the data”. This will present a new and unique problem to the wind energy industry regarding how to tailor previous solutions to larger scale data and opportunities to distil information to then be used in real time. One example of this is in the analysis of vibration data for failures (**?**), another is condition assessment for wind turbine gearboxes (**?**), or predicting failures with weather data (**?**).

Data analytics frequently uses models to help understand data. These models can take many forms. For example, they could be models of a physical process such as the weather, or simulations of goods flowing through a manufacturing plant, or a simple statistical model used for measurement instrument calibration. These models help identify deviations from expected performance given known inputs or forecast future states. The availability of increased computational power allows the use of more complex models, but such models are expensive to operate and maintain and require specialist skills. In contrast, **?** note that “. . . reduced order models (~~ROM~~ROMs) are more desirable due to less computational cost and enough accuracy”. ~~ROM~~ ROMs – often known as “engineering models” – are especially important for real-time or near-real-time applications such as energy forecasting and grid integration ~~. These applications highlight the~~ where fast and/or low-cost calculations are needed. ROMs can take many different forms; they may support wind- or power forecasting on wind farms, where forecasting horizons could be of the order of a few minutes (**?**). They can be used for wind plant design optimization, which often need to run on an analyst’s workstation as those analysts may not have access to high performance computing resources. Similarly, ROMs can also take the form of pre-trained machine learning models or adjoints for uncertainty quantification. For these kinds of scenarios ROMs can be appropriate and more useful than complex models requiring high performance computing. That said, the authors recognize that computational resources and efficiency are constantly evolving and the definition of ROMs needs to be adjusted accordingly. These applications also highlight users’ need for increased model accuracy and speed improvements, ~~not only~~ without requiring additional computational resources. Data-driven and physics-informed models can fill this critical need for faster, less resource-intensive ROMs.

There is also an additional opportunity with federated learning and privacy-preserving machine learning to collaborate across organisations and share results as well as models. **?** explain the introduction of federated learning by **?** as “a decentralized ML approach suitable for edge computing”, with an ability to respond to processing needs. This will bring the ability to advance the wind energy field without the concerns regarding data privacy. Federated learning and privacy-preserving machine learning can enable the deployment and training of a global model system where multiple independent organisations contribute their data (for example, sensor data from a specific wind turbine type) and all users benefit from more accurate models based on more training data, but contributors only ever have access to their own data, as described in **?**.

These new opportunities will bring new challenges. With the opportunity to collaborate across the industry and share more information, questions will arise regarding data ownership and control of models.

4.6 Digitalisation

As noted in the introduction, we define digitalisation as the organisational and industry-wide use of data and digital technologies to improve efficiency, create insights, and develop products and services (Table **??**). Digital technologies typically span from sensing to data management to data analytics to artificial intelligence and automation. In short, ~~it~~ digitalisation is doing new and value-driven things with digital tools.

The previous sections discussed the combination of technical and cultural measures that are needed to bring data to users to assist informed decision-making. They can form part of a workflow that brings data from sensors to users, allows them to make decisions, and then passes information about that decision to other users (as for smartphones) or back to hardware-level actuators (as in the Internet of Things). Although many individual workflows might be digitised and rely on digital objects and data management to get data to users, and then make decisions based on data analytics, this does not mean that the full benefit of digitalisation has been realised, as digitalisation also benefits from network effects. As more organisations undergo a digital transformation, case studies reported in literature suggest they will be better able to interact with customers and other digitalised organisations, ~~forming~~ which in turn leads to more valuable interaction with customers and partners (**???**). This cycle of compounding successes forms a virtuous upward spiral (as opposed to a vicious downward cycle).

~~One challenge with digitalisation is that there is~~

Like all innovations, new digital workflows or products will go through an adoption process. ~~Potential users of digitalised workflows span the usual range from innovators , early adopters , and mass-market through laggards; initial successes by innovators lead to more awareness and increasing adoption, before an innovation becomes “normal” and is used by the mass market. The adoption process therefore needs to happen both within organisations and in the wider~~ This process starts with innovators and early adopters who try something out of curiosity or their own values, followed by later adopters who are driven by economic considerations and thus require some degree of certainty that adopting the new approach is worth the effort (see e.g. **?**). Ultimately, new technologies thrive when they offer a good fit to the social, economic, and technological landscape (**?**). It is reasonable therefore to expect adoption to vary across organisations and across the wind energy industry~~.~~, with some groups being further ahead than others. Sharing experience within and across organisations can help build evidence for the benefits and overcome reluctance to change.

The challenges within organisations relate both to people and culture. We have already noted that adoption of digitalisation will require skills such as computer programming, but it will also require that these be better integrated into existing training for science, technology, engineering and mathematics (STEM) subjects and professional trades. Users will need to be given the opportunity to apply digitalisation—requiring that their organisations support innovation—and will need to be rewarded for their efforts. Furthermore, organisations need to understand the potential value of their data (in all its forms) and develop processes that simplify data-led collaboration. In some cases, these changes may be difficult or disruptive to implement within existing structures, and it may make sense to create in-house incubators, accelerators, or skunkworks to enable innovation.

The wind energy industry needs to explore ways to encourage digitalisation. One way to do this may be to demonstrate the benefits of digitalisation. This could include nationally funded pilot or lighthouse projects but could also include marketplaces to connect innovators and early adopters in rewarding partnerships; one option here may be to (further) open existing marketplaces such as day-ahead energy trading or contract-for-differences schemes and give digital solutions a low-risk environment for testing, where failure or malfunctions have limited or no impact on the rest of the system. These environments are often known as sandboxes. As well as digital sandboxes, hardware testbeds are also required to allow solutions to be trialled in realistic settings where risks can be managed. This could include wind turbines from a few hundred kilowatts through to multimegawatt machines (allowing solutions to be transitioned into products) or even multiple wind turbines within operating wind plants. Importantly, these sandboxes and testbeds would allow benchmarking against traditional approaches, showing the benefits of digitalisation. These initiatives would also have intangible benefits such as increased awareness, developing trust, and creating networks of service providers.

4.7 New products, processes, and businesses

The culmination of digitalisation is new modes of business, new ways of doing things, and new means of interacting with people and machines (**?**). It is more than simply combining all these features into the latest gadgets but is about effective ways of organising human efforts to make the most out of these innovations. Taken all together, these new models lead to "enabling various new forms of cooperation between companies and leading to new product and service offerings as well as new forms of company relationships with customers and employees" (**?**).

New technologies can bring about new businesses, the emergence of failure prediction models, and benefits from predicting failures, but coupled with the open shared data, a few companies can now specialise in failure prediction, providing the service to others and bringing huge economies of scale to the whole industry. Not only is a new company created, but all the clients of the new company receive its benefits. This is particularly the case if digital processes can be turned into software and sold repeatedly (**?**).

Properly resourced and directed research institutions and industry organisations are the start to spurring research connected to real problems in the field. The research funding needs to be willing to fund efforts further along the innovation pipeline to help bridge the so-called "valley of death" that separates research from commercially-relevant products. Industry needs to be properly developed enough to be willing to take risks in reaching backwards across the valley of death. Industry groups need to be well developed enough to guide all actors and instil enough trust and industry guidance to know that their investments will work out and all actors agree on base standards and overall direction.

The organisations need to be designed to be willing to make use of these innovations. **?** discusses how without the capability to innovate their business models, companies will have no means of commercialising their ideas and technology. Organisations must have communication to spread ideas across the company, culture which allows people to speak up, leadership that fosters free thought, and autonomy that allows every employee to act.

Leaders should describe all these efforts in a digitalisation strategy that sets out "a commitment to a set of coherent, mutually reinforcing policies or behaviors aimed at achieving a specific competitive goal" (**?**). These organisational principles are true whether the organisational unit is a company, research institute, or government.

Moving beyond simply implementing new technologies into creating entirely new markets requires an ecosystem of new ideas to develop. For example, without a wide combination of technologies, drones for offshore wind would not be possible. This level of innovation requires coordination across organisations. Drones require battery tech, electronic controls, cameras and sensors, data connectivity, and AI control. The potential market of drones for offshore wind energy applications will bring about numerous companies for the support of all these factors. This is encapsulated by **?**, who define business models as "as a

Table 3. Digitalisation initiatives in the wind energy industry. The examples are illustrative only and not meant as an endorsement; many other alternatives exist.

Type	Activity	Examples
New products	Data marketplaces	Greenbyte marketplace for wind data
	Knowledge sharing	IntelStor Market Intelligence Ecosystem
	Data discovery and sharing	Share-wind.eu metadata catalogue, WP3 Benchmark (**?**), US DOE Data Archive & Portal (**?**)
	Data services from turbine manufacturers	GE Digital Wind Farm Services and Solutions
	Newly enabled products	Falco Drone Technologies used for offshore turbine inspection (**?**)
New processes	Comparison and benchmarking activities	IEA Wind Task 31 (Wakebench; **??**), IEA Wind Task 30 (OC6) floating wind turbine benchmark exercise (**?**), CREYAP: Comparison of Resource and Energy Yield Assessment Procedures (**?**)
	Collaboration platforms	*WeDoWind* data sharing and collaboration platform
	Open-source tools	Brightwind, The OpenOA codebase for operational analysis of wind farms (**?**), Data Science for Wind Energy R Library (**?**)
	Open Data Standards	IEA Wind Task 43 WRA Data Model (**?**), ENTR Alliance, OSDU
New businesses	Data-specific companies	Atrevida Science, WindESCO, Clir, PowerFactors, and i4see
	Companies outside of wind energy applying solutions to wind energy	Uptake applying failure prediction models to wind energy.

management hypothesis about what customers want, how they want it, and how the enterprise can organize itself to best meet these needs, get paid for doing so, and make a profit". The integration of all these aspects, technology, product, customer, and employees, play a part in higher-level digitalisation efforts that provide real value.

How can this vision be implemented in reality? Some of the many relevant initiatives in the wind energy community that aim to bring together all of these needs by sharing data and knowledge to mutually benefit the entire wind energy industry are listed in Table **??**.

4.8 Summary

Based on the previous sections, the key aspects of the digital transformation most relevant for the wind energy industry can be summarised as follows:

- **From digitisation to digitalisation:** The measurement and storage of data that can be used to make business decisions can be time-consuming and expensive, and new methods and systems are required.

- **Digital objects** need to be FAIR so that they can be used effectively in the digital transformation.

- **Big data:** Handling the large amount of data involved in digitalisation requires both semantic and technical solutions. Semantic solutions includes standard metadata and related ontologies, while technical solutions include either new efficient storage systems or new strategies such as linking data distributed across organisations.
- **Data management:** A data management policy concerning the way data are collected, stored, and preserved is crucial for getting the right data to the right users within an organisation, and for data-sharing amongst organisations.
- **Data analytics:** New innovations such as federated learning and privacy-preserving machine learning are required to reduce the computational power required for data analytics applied to big data.
- **Digitalisation:** The new processes and ways of working required for successful implementation of the digital transformation need to be fully adopted by people within organisations.
- **New products, processes, and businesses:** The successful transformation of new findings based on data analytics into new products, processes and business can only happen if research institutes, funding bodies and industry partners actively come together to bridge the valley of death. This could be achieved through new digitalisation strategies.

5 Lessons Learned from Other Networked Industries

Wind energy is characterised by a large amount of dispersed infrastructure that generates lots of data, a flexible network between that infrastructure and other systems, and many different stakeholders. Those stakeholders need access to widely varying data and have different abilities to act within or upon the system, or with each other. Together the wind turbines, stakeholders, and service providers form a digital ecosystem.

These characteristics are also found in other sectors. For example, the Internet of Things (IoT) and smartphones also combine networked hardware, large numbers of users, and large volumes of data. In this section, we examine these sectors and summarise the lessons learned from their specific challenges that could be transferable to the wind energy industry.

5.1 The Internet of Things

The Internet of Things is a web of a multitude of physical objects—things—that are connected to each other, other systems, and users through the internet. It is gradually becoming a reality as more goods are equipped with sensors during manufacturing and can be connected to ubiquitous internet connections. It leverages cheap sensors and easy access to the internet to provide regular data transfer.

The IoT can be thought of as having several discrete layers that facilitate the movement of data between hardware and users, and informed interaction with the hardware (e.g., **?**). These include:

1. The perception layer, where data is obtained by sensors and actuators can act upon infrastructure.
2. The transport layer, where data is collected from sensors and made accessible for processing. Services in this layer also provide secure access to the sensors.

3. The processing layer, where sensor data are stored, aggregated, and interpreted.
4. The application layer, where data is visible to users through specific interfaces, for example for building management, health, or other applications.
5. The business layer, where decisions are made with relation to a person's motives or business's goals.

This ~~layer~~ layered approach allows data to be transferred ~~up to users and back to~~ back and forth between users and actuators through specialist service providers. A user can then use vertically integrated solutions or combine different services (potentially with the help of an integrator) to get the solution that they need.

The IoT enables many different applications, including vehicle fleet monitoring, automated inventory management, and monitoring national infrastructure. It also has applications for consumers, for example for access passes at entertainment parks ~~(e.g., Disney's "Magic Band" ?)~~ (e.g., Disney's "Magic Band"; ?) or for order-on-press buttons (e.g., Amazon's "Dash" button). And, the internet of things is already enabling wind turbine condition monitoring (**?**).

Adoption of the IoT has not been uniform. The major challenges to adoption reported in a 2016 survey included (in descending order of frequency) privacy and security concerns, the cost, lack of knowledge about solutions, inadequate infrastructure, lack of standards, interoperability concerns, uncertainty that it will deliver the promised benefits, poorly defined workflows, and immature technology (**?**). The same challenges should be expected for the digitalisation of wind energy, which is in many ways just an application of IoT approaches.

5.2 The smartphone hardware and software ecosystem

Smartphones are small, portable computers with an internet connection. They run specialised applications or "apps" to carry out a wide range of tasks, from telephony to web browsing, shopping, participating in social networks, and for many other purposes.

The apps run on the smartphone's operating system. The apps leverage other apps or service providers to identify users, manage their rights to interact with the app, and charge them for services. From the user's perspective, this is mostly seamless, and improvements can be made by modifying software, so long as the hardware is flexible enough. Apps allow consumers to pay for what they consider important and customise their smartphones to meet their needs. Consumers have demonstrated their willingness to ~~pay for~~ spend on apps: in ~~2020 582~~ 2021 just under 190 billion USD of revenue was generated ~~through apps alone.~~[1] by app purchases and subscriptions (**?**).

In the early days of smartphones, vendors often created "walled gardens" in that each vendor had their own operating system, effectively locking customers and software developers into that platform (**?**). Today, smartphone vendors instead use several common operating systems, allowing software developers to target the operating system and not the vendor, and enabling customers to keep their apps and data, even if they change vendor. Those smartphone businesses that are vertically integrated in that they develop and sell smartphone hardware, operating systems, and apps, almost all allow third-party services to be run

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[1] ~~https://www.statista.com/statistics/269025/worldwide-mobile-app-revenue-forecast/~~

on the handset or operating systems. This change was in response to consumers requiring interoperability across hardware, and the growth of providers who provide apps for multiple operating systems. However, it has also raised concerns about the ability of handset manufacturers to access data stored on those devices.

The smartphone market includes traditional business-to-consumer (B2C) services such as selling the phone hardware, selling one-time services (e.g., apps), subscription services, as well as disruptive innovation and experimentation (e.g., Uber and Instagram). It also includes large business-to-business (B2B) services, for example selling network infrastructure, hardware components, software, and back-office services. In ~~2020~~2021, around 1.4 billion handsets were sold for ~~around 400 billion USD ,~~[1] 481 billion USD (??), while the telecom network equipment ~~was worth another 500~~ market was estimated to be around 539 billion USD in ~~2020.~~[1] ~~Each of these related markets grows~~ 2021 (?). These related markets grow at between 2% and 10% per year as technologies are updated, new businesses are launched, and customer expectations change.

5.3 Lessons for the future wind energy digital ecosystem

The relevant lessons learned from the examples above can be summarised as follows:

1. The digital future will be dynamic, with an unpredictable mixture of actors and technologies.
2. There will be very few, if any, vertical solutions that directly connect the user with the hardware. Instead, most interactions will be between one layer and the next.
3. Standards about interaction between and within different layers will be required to avoid market fragmentation.
4. Specialist service providers will develop to support activities. These may be within a single layer, or link one layer to the next.
5. Services such as user authentication, permissions management, intrusion detection will be essential for safe and reliable operation of the system.
6. Innovation will happen in unexpected places and will take unexpected forms.
7. It will involve a competitive, but collaborative, community.

These lessons learned should also be considered by the wind energy industry as it undergoes its digital transformation.

6 The Grand Challenges

In this section, we first describe how we identified the Grand Challenges, and then we introduce them.

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[1] ~~https://www.statista.com/topics/840/smartphones/~~

[1] ~~https://www.verifiedmarketresearch.com/product/telecom-equipment-market/~~

6.1 Methodology for identifying the Grand Challenges

The Grand Challenges for the digitalisation of wind energy were identified by:

1. Consideration of the conclusions from the previous sections of this paper.
2. Further stakeholder data collection, including (a) data sharing interviews and ~~around~~ (b) diversity in wind energy.
3. Combination of findings from steps (1) and (2).

These steps are described ~~further,~~ in more detail below.

6.1.1 ~~Consideration of the conclusions from the previous sections of this paper~~

Step 1: Consideration of previous conclusions

The conclusions from the previous sections of this paper that are relevant for identifying the Grand Challenges include:

- **Data:** A data management policy concerning the way data are collected and stored and preserved is crucial for getting the right data to the right users within an organisation and data sharing amongst organisations. The measurement and storage of data that can be used to make business decisions can be time-consuming and expensive, and new methods and systems are required. To utilise data effectively for the digital transformation, it needs to be FAIR. The large amount of data involved in digitalisation means that new, efficient storage systems and agreed-upon metadata standards are required. New innovations such as federated learning and privacy-preserving machine learning are required to reduce the required computational power of data analytics applied to big data. Services such as user authentication, permissions management, intrusion detection will be essential for safe and reliable operation of the system.
- **Culture:** The digital future will be dynamic, with an unpredictable mixture of actors and technologies. Innovation will happen in unexpected places and will take unexpected forms. The new processes and ways of working required for successful implementation of the digital transformation need to be fully adopted by people within organisations.
- **Coopetition**: The successful transformation of new findings based on data analytics into new products, processes, and business can only happen if research institutes, funding bodies, and industry partners actively come together to bridge the commercialisation valley of death. This could be achieved through new digitalisation strategies. There will be very few, if any, vertical solutions that directly connect the user with the hardware. Instead, most interactions will be between one layer and the next. Standards about interaction between and within different layers will be required to avoid market fragmentation. This will require a competitive, but collaborative, community.

Considering the conclusions from the previous sections of this paper allows us to make two further observations relevant for identifying the Grand Challenges. The first is that, despite the issues identified in the stakeholder interviews and in this paper,

Table 4. The top five barriers to data sharing. These barriers were identified from the second interview series.

Rank	Owner/operators	Academia	Technology providers
1	Getting all the data in one spot	Lack of public data	Data quality (completeness, validity, etc.)
2	IT issues: servers, etc.	No standard format for analysing and processing data	Different format and structure of data
3	Cleaning/filtering raw data (different time scales and resolutions, different formats)	Poor data quality	Data filtering for analyses
4	Refining and processing data ready for machine learning model (80% of time)	Lack of willingness to share data, especially higher resolution	Data collection; different devices need to be programmed differently
5	Interfaces to collecting data reliably	Lack of change logs	Time for downloading, cleaning, and training data

the digitalisation of wind energy is already progressing. Some organisations have made progress in adopting it for parts or all of their businesses. Evidently, the challenges identified by the survey and expert elicitation can be mitigated, and the technical solutions required for digitalisation must exist. Therefore, “the future is already here — it’s just not very evenly distributed” (attributed to William Gibson, possibly apocryphal). The second observation is that, because of its cyclical and transitional nature, the process of digitalisation will never be complete.

6.1.1 ~~Data collection activity A: data sharing interviews~~

Step 2(a): Data sharing interviews

The data collection activity focused on the specific barriers seen by the wind energy sector in the actual implementation of digitalisation. For this, a total of 30 members of the global wind energy sector were asked to describe their main barriers to data sharing in individual interviews lasting approximately one hour. This included seven owner/operators, seven researchers, and sixteen technology providers from the wind energy industry. This specific question was asked because it has already been established that the topic of data sharing and reusing is one of the central challenges in the implementation of digitalisation in wind energy (Figure **??**). The survey was done as part of the activities of IEA Wind Task 43 Technical Area 2. The results are summarised in Table **??**. This shows the five barriers with the highest frequencies of occurrence for each interviewee type. Some of the barriers are quite similar between interviewee types, in particular the topics of (a) standard data format/structure, (b) data availability and quality, and (c) data processing/preparation time.

Other barriers that came up frequently but did not make the top five include:

- ~~Unclear intentions of OEMs /~~Wind turbine OEMs can make unannounced changes to ~~controllers.~~ the controller or be difficult to communicate with

- ~~State-of-the-art in data science not clear, no place where work is well-summarised~~It is difficult to access the most state-of-the-art tools and models, and there is no central location summarising the relevant information.
- ~~Differences between different analysts. What really works and what's really applicable?~~ Analysts have different methods, skills sets, and working styles. It is hard to identify what actions will really have an impact.
- ~~Data security and privacy~~ Concerns about data security and data privacy related to both personal data and confidential information
- ~~Finding the right people who can do~~ It is challenging to find people who are capable of both data analytics and ~~have the required domain knowledge.~~ understanding the operation of wind turbines

It should be noted that these findings generally agree well with the literature survey in Section **??**. As well as this, it is interesting that most of these barriers are related to company culture, people skills, and communication between different people. These aspects should therefore be included in any discussion about the digitalisation of wind energy, and this is the topic of the second interview series described below.

6.1.1 ~~Data collection activity B: diversity in wind energy~~

Step 2(b): Diversity in wind energy

We have shown that some of the key barriers to the successful implementation of digitalisation in the wind energy industry are related to company culture, people skills, and communication between different people. This raises the topics of ~~Diversity, Equity, and Inclusion~~ diversity, equity, and inclusion (DEI). ~~Diversity is any characteristic that can be used to differentiate groups and people from one another, and thus DEI is about respecting and valuing the aspects that make people different~~ In this context, "diversity" refers to involving people from a range of different backgrounds (social and ethnic) and of different ages, genders, religion, ~~for example in terms of age, gender, ethnicity, religion, disability, sexual orientation, education, and national origin.~~ sexual orientations, disabilities, education, nationality, and others. "Equity" refers to the quality of being fair and impartial, and "inclusion" refers to providing equal access to opportunities and resources for all. DEI is an increasingly important topic especially in technology- and innovation-based industries.

To examine this topic in more detail and in the context of the wind energy industry, a second data collection activity was carried out by the Diversity Committee of the European Academy of Wind Energy (EAWE). This data collection was focused around ~~two main events:~~ a DEI panel discussion at the TORQUE 2020 conference and a DEI workshop series.

The TORQUE 2020 panel discussion was postponed due to the COVID-19 pandemic and actually took place in June 2021. A literature survey carried out in advance of the event showed that technical workforces in general do not represent the general population's diversity in race, gender and sexual orientation. For example, women represent only 21% of the global wind energy industry's workforce and only 8% of its senior management (**?**). This is known as "under-representation". It is a problem because the literature survey also found that diverse teams are more productive (for example, gender diverse companies are 15% more likely to outperform their respective national industry medians) and that diversity is good for business (as diverse companies are 35% likelier to financially outperform the industry medians). The panel discussion, and audience contributions from more than 50 members of the wind energy research community during the event, revealed that the community generally sees and understands the benefits of increasing diversity in wind energy, but many people do not know how to contribute. The expert panellists made some suggestions about how to contribute, including sharing facts and stories with each other, noticing and correcting one's own unconscious biases, and ensuring diverse recruiting teams.

Around 30 wind energy professionals took part in the DEI workshop series. As in the panel discussion described above, it was found that many people simply do not know how to contribute to improving diversity. The main DEI challenges of the wind energy community were found to be (1) attracting, (2) recruiting and (3) keeping a diverse range of people as well as (4) ensuring a diverse range of people in higher management. Possible solutions to these challenges suggested by the community included organising specific diversity events at conferences and trade fairs, providing a platform for sharing experiences, developing recruiting guidelines, providing diversity training / education for team leaders, providing mentoring schemes, networks and role model events and providing a framework for proactive hires, exchange programmes, female-only positions, and others.

In summary, the main findings of this data collection activity were that (a) diversity has to be improved in the wind energy industry in order to successfully exploit the advantages of digitalisation, and that (b) concrete steps are already being undertaken by the wind energy industry in order to achieve this goal.

As far as the authors are aware, the specific topic of diversity in wind energy digitalisation has not yet been studied. However, discrimination of under-represented groups caused by digitalisation has been well documented - for example, digital technologies are trained on male-biased data (**?**) or existing recruiting patterns that support homogeneous workforces. These technologies then recreate and reinforce these patterns. This is known as the "digital divide" (**?**). This topic should be further investigated in connection to wind energy.

6.1.1 ~~Combination of findings~~

Step 3: Combination of findings to identify the Grand Challenges

Based on the observations and interview results presented above, we ~~therefore propose~~ propose the following three Grand Challenges ~~for digitalisation that are joined in~~ in the digitalisation of wind energy.

1. Data: creating FAIR data frameworks
2. Culture: Connecting people and data to foster innovation
3. Coopetition: Enabling collaboration and competition between organisations.

These challenges form a cycle that combines the process of technology ~~transitions (as discussed in Section **??**~~transition (Section **??**) and technology adoption (**?**). In this cycle, data are made available, the data are then used as the basis for innovation, and the innovations are ~~brought~~ bought to market. ~~The Grand Challenges associated with each of these steps are the need to:~~

1. ~~Create reusable data frameworks~~

2. ~~Connect people to data to foster innovation~~
3. ~~Enable collaboration and competition between organisations.~~

As a result, more data become available and the cycle repeats. These Grand Challenges are described in more detail in the following section.

6.2 ~~The~~ Defining the Grand Challenges

6.2.1 ~~Data: Creating FAIR data frameworks~~

The three Grand Challenges in the Digitalisation of Wind energy are:

1. Data: Creating FAIR data frameworks

Digitalisation is, at its root, the ability to act upon data. An example of this is a decision making processes that brings together many different data sources, analyses them, and takes decisions around that data. Because the same data might be used by many different actors and for many different purposes, the data need to be FAIR.

The interviews presented in Section ~~??~~ ?? confirmed our experience that much of the data generated in the wind energy sector today are not reusable because they are not documented by metadata and thus remain isolated or siloed within organisations or data stores, simply not findable. In the initial interview round, it was noted that one of the main barriers for a successful digital transformation is the “lack of data standards and interoperability”. This is a well-known problem, and policy leadership by governments, public bodies, and organisations is helping to mitigate this (e.g., **?**). The growing requirement by funding agencies for data management plans for research projects is helping to train the next generation of wind energy sector researchers to think about data. Reporting requirements also help generate the data that are needed, for example from the U.S. Energy Information Administration about plant construction and performance (the IEA 860 report) or the North American Electric Reliability Corporation (NERC) reports about generator availability (the NERC GADS reports).

As noted in the interviews, an opportunity for overcoming the challenge of the findability of data is to implement “top-down policies such as FAIR data requirements for scientific journals and research projects”. As introduced in section 4.2, this implies the need for agreed standard metadata schema and related ontologies to help navigate the wealth of data. There have been some efforts to produce these standard metadata schema and related ontologies e.g., by the IRPWIND project and through activities in IEA Wind Tasks 32, 37, and 43. However, making them converge, bringing them to a maturity level and spurring community adoption needs a concerted effort and sector-level collaboration. This is one example of how reusing data can be considered a grand challenge.

Reusability also requires ways to get data to the right users at the right time. Once data has been found, it needs to be made accessible to users. This applies equally within organisations and outside of organisations. While internal data access is an organisation’s own challenge to deal with, the wind energy industry needs to improve access to data at the sector level, and the interviews revealed that especially industrial stakeholders saw an opportunity in “data markets allowing access to data, which even can be paid for”. As noted earlier, this access to data can often be essential for innovations (**?**).

Although they are required to incentivise data sharing, marketplaces for digital services are rare. Some marketplaces exist for data, such as the U.S. Atmosphere to Electrons (A2e) data archive and portal (**?**), while the prototype of the *sharewind.eu* metadata registry from EERA JP Wind launched in 2017 has been upgraded to a FAIR searchable data catalogue called *sharewind.com* by the H2020 Coordination Action project *FarmConners* and is being populated by different projects. These markets are focused on discovering existing data, rather than buying or selling data. First steps are being taken to make high-frequency real-time data available, which will be essential for more flexible operation of wind turbines and wind plants. True markets for digital services (i.e., where services and data can be bought and sold) are needed so that innovators and early adopters can try them out and develop processes that the majority can then benefit from. Like other new markets, these will probably be small, illiquid, and unprofitable at first and need some time to generate enough users to be effective. Therefore, national or sector funding may be required to support the initial growth of data and service markets.

It is our opinion that the difficulty of making data reusable across organisations~~, and~~ ; the need to collaborate to provide the framework to do so~~,~~ ; and the potentially huge reward as a result, makes ~~reusing~~ creating FAIR data into a Grand Challenge for the wind energy industry.

6.2.1 ~~Culture: Connecting people and data to foster innovation~~

2. Culture: Connecting people and data to foster innovation

It has become clear in this paper that reusing data alone will not allow the full potential of the digital transformation to be exploited in the wind energy industry. As expressed in our qualitative data collection, digitalisation and digital R&D succeeds when connecting data with models with people. This can be done, for example, by developing and maintaining new types of organisational cultures, by combining staff skills and training needs in new ways, enhancing communication skills, working together on new types of innovation and change processes, and by increasing diversity. However, a frequent point mentioned in the interviews was that "organisational change and change management are the biggest challenges. . . of digital transformations".

Digitalisation is also a change to established ways of working. One interviewee's comment captured the consensus from many others by noting that "researchers require more digital skills, and furthermore a stronger collaboration with software developers". It can require new skills from individuals (e.g., computer programming); new ways of thinking (modular and collaborative, as opposed to siloed); and new infrastructure (cloud computing and distributed teams, rather than centralised services). It also requires organisations to embrace open innovation styles such as co-developing new digital products or reconfiguring existing processes to enable new business ideas. And organisations need to bring these innovations to market, while the market needs to be willing to accept new products or services.

The interviews described in Section ~~**??**~~ **??** confirmed that some of the key barriers to adopting these new ways of working are actually part of the organisation's own culture, and furthermore in the strategy and perception of other actors. Overall, and regardless of the respondents' background, open innovation and open-source paradigms were determined to be key levers for success with the digital transition.

Organisations that can change their culture become well-placed to benefit from digitalisation, while organisations that are less able to change risk losing innovative staff to other organisations that can support them. Such support can take many and varied forms that aim to align internal creativity with the organisation's mission, leading to new products and services (**?**). There are many well-established ways to train staff in new skills, change existing corporate culture, or establish new corporate cultures. Therefore, we do not see the process of corporate change *per se* as a Grand Challenge.

Similarly, there are many well-established ways for governments to reduce the risk of innovation. Governments can help to reduce financial risk by reducing the cost of innovation through grant funding, tax credits, and many other means. Governments and regulators can also help open the window of opportunity by establishing the right market conditions and by providing safe spaces to trial new technologies, such as specially developed infrastructure.

Instead, it is important to recognise that digitalisation is different from other innovation and change processes because it relies on bringing data and people together to trigger and support innovation. Therefore, organisations need to provide the internal processes for people to access and explore data, mechanisms for these innovations to be identified and nurtured, and spaces to try out their ideas in a business context. Governments and regulators can also support this by creating sandboxes—real or virtual infrastructure—that can be used for pilot projects, and as expressed by a respondent, "understanding that this data revolution brings the energy industry to an inflection point" where regulatory support is required. These are often national or flagship facilities such as NREL's Energy Systems Integration Facility (ESIF) but can also be regional infrastructure.

In the surveys carried out as part of this paper, a common desire among the respondents, regardless of job title, company type, and geographical location, was to enhance the opportunities for collaboration amongst the diverse actors in the energy industry, and beyond. And, improving diversity, equality, and inclusion in the wind energy sector may increase the effectiveness of that collaboration. Long-term initiatives to increase gender equality and increase the workforce diversity are therefore essential to the future success of digitalisation.

We consider the need to connect people and data to foster innovation as a sector-wide Grand Challenge, as it impacts nearly all organisations in the wind energy sector. It requires organisations to offer new approaches to doing business, their customers and partners to request and support these innovations, and government support to be successful. Establishing innovation cultures inside organisations therefore needs collaboration between many stakeholders on a wide range of initiatives, making this a sector-wide challenge.

The result of overcoming this Grand Challenge will be organisations that have innovation cultures (either in parts or as a whole) and can thus respond to the changing landscape around them. This will be an essential characteristic both to drive digitalisation and to benefit from it.

6.2.1 ~~Coopetition: Enabling collaboration and competition between organisations~~

3. Coopetition: Enabling collaboration and competition between organisations

Addressing the Grand Challenges of reusing data and creating innovation cultures within organisations provides the basis for digitalisation within organisations or narrow sectors. However, one of the biggest potentials of digitalisation is that it allows artificial barriers to be broken down.

Our final grand challenge is therefore to enable cooperation, collaboration, and competition between organisations. This means working together to create marketplaces or business opportunities that would not otherwise exist and that are mutually beneficial. This has happened in other businesses; possibly the best-known example of this is the Bluetooth standard for short-range wireless data exchange, which grew out of collaboration between device manufacturers in the 1990s. This process is sometimes known as coopetition or co-creation and is the antithesis of vertical integration in which internal R&D leads to internal development, production, and distribution.

There are several steps to be taken before this can occur across the wind energy sector, which we define based on our experience combined with the results of the interviews described in this paper. The first is to simplify the process of cooperation across organisations by streamlining nondisclosure agreements, licensing, and other nontechnical barriers to cooperation. Together with making data reusable, this will mean that the barriers to cooperation are reduced, and is more likely to happen within small, trusted groups initially (e.g., the UK Open Energy initiative). This may turn into a “race to the bottom,” as streamlined organisations are easier to collaborate with, and once one business starts the process, others must follow or risk being side-lined.

The next step is to set up liquid, easily accessible markets where innovative, collaborative organisations can meet customers. Such marketplaces will likely make extensive use of metadata, sector-level taxonomies, standardised virtual environments, and open-source data libraries to make their services easily findable, interoperable, and reproducible. Data itself is likely to become a more widely traded commodity. There will be a need for data providers, marketplaces, and data users to implement processes to keep data up to date and maintain interoperability. These processes could leverage approaches used in the software community for open-source software versioning, distribution, and compatibility monitoring (e.g., GitHub.com, ~~or PyPI~~PyPI, and others). Otherwise, there is a risk of data becoming unusable, irrelevant, or even misleading over time.

The final aspect of this Grand Challenge is the need to help all stakeholders understand the potential for digitalisation. This could take many forms, from clearly communicating the results of research projects to benchmarking new tools against established ways of doing things, or even by businesses sharing the need for certain new tools. All of these factors together will help generate demand for the new businesses arising from digitalisation.

Together, simplified cooperation across organisational boundaries and liquid markets makes the collaborative promise of digitalisation a reality. However, these are not the final step in digitalisation; making progress on any of these three Grand Challenges creates the potential for more innovation, new businesses, and new opportunities for coopetition. Therefore, we consider the Grand Challenges to be cyclical, rather than an end-to-end process.

~~These Grand Challenges must be continually overcome so that the wind energy industry can reap the benefits of digitalisation, such as reduced costs, improved performance, increased safety, and new business models.~~

7 Conclusions

In this paper, we have ~~defined~~ identified three Grand Challenges in the digitalisation of wind energy. This was done by first exploring digitalisation as a key pathway for the wind industry to be a cornerstone of a decarbonised, low-cost energy future. Ongoing digitalisation efforts across the wind energy industry were used as examples to identify some of the opportunities and challenges that the industry faces. They also show that the digital wind plants of the future ~~will~~ could utilise a host of technologies such as sensors, data, analytics, digital twins, and ~~even automation~~automation, but require clear value propositions to help drive adoption. These technologies will improve safety, efficiency, and reliability, all while reducing costs. The vision of the future in this paper is further informed by collaborative research and expert elicitation across many sectors of the industry. This research has helped illuminate the current state of the industry and critical barriers to overcome. Next, we put forward a more detailed and consensus definition of digitalisation to help readers understand the digital transformation and the key concepts underpinning it, as well as to help us define the Grand Challenges in the digitalisation of wind energy. We also looked at examples from other industries that can help us accelerate through the learning curve. We find that walled gardens and vendor lock-in prevent innovation ecosystems. However, ecosystems that are open enough to have common data formats and interoperability can lead to new business models, rapid adoption, and best-in-class offerings.

Digitalisation of the wind energy sector offers increased reliability, cost savings, new business models, and cost-effective integration of wind energy as an energy source. But it brings three Grand Challenges that need to be solved. These are:

1. Data: Creating ~~reusable~~ FAIR data frameworks
2. Culture: Connecting people and data to foster innovation
3. Coopetition: Enabling collaboration and competition between organisations.

Addressing the first two Grand Challenges for the digitalisation of wind energy provides the right conditions for sector-wide adoption. Then, the third Grand Challenge brings together actors to make progress. Addressing these Grand Challenges creates a virtuous circle that would lead to increasing digitalisation and increasing benefits to the entire wind energy industry such as reduced costs, improved performance, increased safety, and new business models.

Solving these Grand Challenges will require contributions from a variety of stakeholders. To that end, we highlight recommendations for individuals and organisations in Table **??**. These recommendations were informed by the literature survey and expert interviews presented in this paper.

These recommendations for ways to address the Grand Challenges in the digitalisation of wind energy provide a framework for a more efficient, inclusive, and innovative wind energy industry. They are only the beginning of a dynamic process that will position wind energy as an essential part of a global clean energy future.

Table 5. Recommendations for how different organisations - businesses, research organisations, and funding agencies - could address the Grand Challenges in the digitalisation of the wind energy industry by setting strategic goals and through specific implementation actions.

Grand Challenge	Strategic Goals	Implementation Actions
Data	– Organisations should implement tools and frameworks to maximise the value of their data	– Funding agencies should require that all data collected and produced be FAIR – Scientific publishers should require FAIR digital objects (data, code, etc.) – Organisations should participate in sector-level collaboration to define and adopt universal data standards and schema – Funding organisations should support the creation of infrastructure for data and digital service marketplaces built on FAIR practices – Businesses and research organisations should provide ways for internal and external stakeholders to access and explore data efficiently – Organisations should ensure that data systems follow cyber-security best practices
Culture	– Digitalisation should be a common thread throughout an organisation's activities. It should be supported by recruitment, (re)training, removing barriers to adoption, and staff evaluation – Organisations should align digital initiatives with their mission, leading to new products and services – Digital initiatives should be people-focused and prioritise stakeholder buy-in as a precondition for success – Businesses should create cultures that allow new types of innovation and change processes to be tried and tested in safe environments – All stakeholders should actively engage in measures to increase DEI to maximise both participation and the potential for digital innovation	– Businesses should provide teams and team leaders with the resources to enhance their communication skills – Businesses should implement DEI best practices such as developing recruiting strategies, mentoring programs, and personnel training – Funding agencies should fund further research on the needs of under-represented groups specifically affected by the digitalisation of wind energy – Funding agencies should help show the potential for digitalisation by funding open data and benchmarking datasets – Organisations should create sandboxes that can be used for pilot projects
Coopetition	– Organisations should support the development of a common core of open-source tools and frameworks which can accelerate innovation and collaboration across the industry	– Businesses and funding agencies should support the creation of common open data standards – Businesses should simplify the process of cooperation by streamlining nondisclosure agreements, licensing, and other nontechnical barriers to cooperation – Governments, sector bodies, or businesses should set up liquid, easily- accessible markets for data and digital services where innovative, collaborative organisations can meet customers – Governments and regulators should encourage transparent public energy data which protects personal privacy whilst facilitating innovation and benchmarking – Businesses and funding agencies should support R&D projects that showcase the use of data marketplaces and public energy data – Organisations should embrace public and private benchmark projects, tools, and datasets to quantitatively show the benefits of digitalisation

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Disclaimer. The mentioning of any company, brand, product, or service in this paper is purely by way of an example and should not be taken as an endorsement or recommendation.

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