UK Energy Sector Digital Adoption: A Local and Global Comparison

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Technology Driving Transition

Executive Summary

With a global drive to a Net Zero future, countries and companies worldwide are developing their decarbonisation strategies with the growing recognition that digital technologies are a key ingredient necessary for the success of their plans. The energy industry is at the forefront of this drive, and while the importance of digitalisation in achieving Net Zero is broadly recognised, the impact and benefits of digital technologies can only be realised if these technologies are adopted.

The Purpose

Despite many reports on the role digitalisation plays in the transition to Net Zero, there is less research on the levels of digital technology adoption.

The report examines the current levels of digital technology adoption - specifically artificial intelligence (AI), digital twins, robotics, cybersecurity, and remote operations - within the United Kingdom's industrial energy sector, benchmarking against international energy sectors and, at a high level, against other sectors. The report provides a gap analysis between the UK energy industry and the international benchmarks, identifying key gaps and areas of improvement.

The primary analysis spans across key energy sectors, including oil and gas, hydrogen, nuclear, geothermal, carbon capture utilisation and storage (CCUS), wind, solar, hydro, wave and tidal, and examines their application throughout the entire energy lifecycle, encompassing production, storage, transport, and utilisation.

This report is subjective by its very nature as it relies on largely desktop research and the review of many hundreds of published documents, reports and studies. It aims to provide an overall perspective relating to adoption of digital technologies, but more detailed analysis would require extensive industry interviews and surveys.

This report, commissioned by Scottish Enterprise and delivered by the Net Zero Technology Centre, fills that gap and examines the important role that digital adoption plays in the UK Energy Industry.

Key Findings

The findings reveal a varied landscape of adoption, with the oil and gas industry showing higher levels of adoption in comparison to the other, less mature, energy sectors. However, when looking at international and cross-industry comparisons, the UK energy industry's digital adoption efforts have focused on a shallow spread of accessible and known use cases. Comparing the levels of digital adoption and performance observed in high-performing countries and industries, it's clear that the UK Energy Industry is still lagging, with room for continued improvement.

While UK and Scottish Governments have actively promoted digitalisation through a variety of initiatives and funding schemes, implementation and integration of these technologies are influenced by factors such as sector-specific challenges, technological maturity, and economic viability.

The report outlines general trends in adoption, identifies challenges including data silos, skills gaps, and regulatory uncertainties, and notes the potential for efficiency improvements, sustainability advancements, and cost reductions that digital transformation can provide.

The analysis includes global best practices from leading countries and industries, along with practical recommendations for the UK energy industry to act upon to accelerate the adoption of digital technologies in support of their energy transition and net-zero ambitions.

The UK Energy sector is a mature industry with a level of digital maturity to match. From the analysis in this report, and other industry reports, it would be understandable to draw the conclusion that levels of digital adoption are also mature. Indeed, there is a wide spread of digital technology adopted but this breadth is not matched by the depth of adoption required to unlock digital's full potential.

The UK energy sector continues to take a traditional approach, while other industries and international sectors embrace digital transformation. Norway leads in digital adoption in the energy industry, ranking higher than the UK in both the IMD Digital Competitiveness Index and WEF Energy Transition Index. Their extensive use of digital technology boosts their competitiveness and energy transition performance.

There is a very clear correlation between those countries that feature in the highest ranks of the Energy Transition Index and those that have a high ranking in Digital Competitiveness. The inference therefore is that strong digital adoption has a significant impact to the acceleration of energy transition. This is supported by two remarks made during a World Economic Forum session held in Davos entitled Energy Outlook: Overcoming the Crisis.[1]

The opportunity is clear: fully commit to digital transformation and drive digital adoption to improve the digital competitiveness and energy transition performance of the UK on the world stage. The UK energy industry has the fundamentals in place, but it must go deeper on the recommendations outlined in this report to capitalise on this opportunity. Progress is being outpaced by the rapid advancement of digital and AI and is typically made by individual companies with limited time, resource and budget. It's not coordinated, it's less strategic, it's slower, it's difficult and it's delivering limited benefits.

The UK energy industry must unite in advancing digital technology, acknowledging its strategic significance in achieving net-zero emissions, while cooperating on the various focus areas highlighted in the recommendations of this report.

> **"Deep decarbonisation is not possible without digital."**
>
> **Zoe Yujnovich,**
> **Shell's Upstream Director**

> **"There is no green without digital."**
>
> **José María Álvarez-Pallete López, CEO of Telefónica**

[1] Recharge (2022), 'Europe must embrace "green digital" to disrupt and drive the energy transition'

Key Findings

The key summary and findings from each of the five main sections of this report are outlined below.

1. UK Energy Industry Benchmark

The analysis highlights varying levels of digital adoption across the UK energy sector, with established industries like oil and gas demonstrating higher integration compared to emerging areas such as hydrogen, CCUS, and wave/tidal technologies. Key technologies, including AI, digital twins, remote operations, and robotics, show differing maturity levels, with AI and digital twins more widely adopted in wind, solar, nuclear, and fossil fuel sectors, while robotics remains nascent due to reliability challenges. Cybersecurity emerges as a critical priority across all sectors. Factors such as sector maturity, asset deployment, and regulatory drivers influence adoption rates, emphasising the need for tailored approaches to accelerate digitalisation and support net-zero ambitions.

2. UK Cross-Sector Comparison/Benchmark

Digital adoption across sectors in the UK varies significantly. Industries like finance, aerospace, automotive, manufacturing, and pharmaceuticals have achieved advanced integration of technologies such as AI, automation, IoT, and digital twins. This progress is largely driven by consumer demand, innovation, and compliance with regulatory standards. In contrast, the energy sector takes a more structured, government-led approach, focusing on technologies like smart grids and digital twins to meet net-zero emissions targets. However, smaller companies in the sector face challenges such as high costs and fragmented data.

By examining industries like finance and pharmaceuticals, valuable lessons can be learned. Sharing best practices in areas such as upskilling, cybersecurity, and data management could help overcome barriers to digital transformation. This would enhance efficiency, lower costs, and strengthen the UK's competitiveness on the global stage.

3. International Comparison/ Benchmark

The benchmarking analysis highlights how countries like Norway, Germany, USA, South Korea, Japan, and Singapore demonstrate advanced digital maturity and integration within their energy sectors. Norway excels in digital adoption through coordinated governance, shared data platforms, and long-term investments, making it a model for system-wide transformation. Germany leverages Industry 4.0 principles across sectors, fostering collaboration and innovation, though adoption in traditional energy remains uneven. The US leads in robotics and AI within energy systems, showcasing the importance of large-scale experimentation and public-private partnerships. South Korea and Japan focus on nuclear digitalisation and robotics, with South Korea's workforce development driving significant advancements, while Singapore exemplifies rapid implementation through agile governance and integrated infrastructure.

Across all the examples, successful digital adoption is enabled by long-term investments, government-industry collaboration, workforce development, and operational integration. While the UK performs well in energy transition rankings, its digital readiness lags, undermined by fragmented strategies and low workforce training scores. Lessons from global leaders emphasise the need for cohesive governance, targeted investment, and skill development to transform the UK's innovation potential into widescale operational success.

4. Gap Analysis (UK strengths/weaknesses)

The UK has strong potential to lead in the digital energy transition but faces structural and operational barriers. Despite impressive innovation capabilities and policy frameworks, its energy sector lags behind in scaling digital technologies, hindered by fragmented governance, insufficient workforce skills, and outdated infrastructure. National rankings in digital competitiveness highlight key weaknesses, including low investment in communications infrastructure, inadequate employee training, and limited adoption of advanced digital tools across industries.

To bridge the gap between capability and adoption, the UK must focus on developing digital skills through tailored training programs, accelerating infrastructure investments for technologies like smart grids and 5G, supporting scale-ups that offer industrial solutions, and establishing a unified governance strategy to align innovation clusters with broader infrastructure and policy efforts.

5. UK Barriers to Adoption

Digital adoption in the energy sector faces numerous barriers that hinder its progress. Resistance to change remains a significant challenge, as organisations prioritise risk minimisation over innovation, with concerns about job security further limiting adoption. Cybersecurity risks are heightened by immature connectivity, exposing critical infrastructure to vulnerabilities. Additionally, siloed data, poor data management, and a lack of mature strategies impede the use of analytics and digital technologies. High investment costs, unclear business cases, and outdated assets further discourage adoption.

Other critical barriers include a shortage of digital skills, fragmentation in data sharing, and the absence of industry-wide standards, which limit interoperability and innovation. Disparities in organisational size and varying capabilities in research and development contribute to inconsistent progress. Collaboration remains weak due to competition among operators, and compatibility issues with partners and older systems exacerbate challenges.

To overcome these obstacles, the energy sector must focus on developing clear strategies, fostering collaboration, and enhancing skills and infrastructure to fully realise the benefits of digital transformation.

Key Strategic Recommendations

Key Findings

The strategic recommendations, presented below, are derived from the comprehensive findings of the report. They address the major barriers identified and include additional suggestions to accelerate digital adoption in the UK energy industry.

To accelerate the adoption of digital technologies in the UK industrial energy sector, the following recommendations are proposed. The challenge for the energy sector is being able to progress these as a sector, as opposed to individual company-specific solutions.

Digitalisation is not an optional add-on but a core enabler of the UK's 2050 energy ambitions[2]. It is essential for integrating renewables, maintaining security, reducing costs, empowering consumers, and achieving net-zero emissions. The government's strategy and action plans are focused on accelerating digital adoption, building the necessary infrastructure and skills, and ensuring the regulatory environment supports innovation and flexibility across the energy sector.

Both the International Energy Agency (IEA)[3] and the International Maritime Organisation (IMO)[4] highlight digitalisation as a key driver for the global energy transition, recommending the integration of digital technologies to enhance efficiency, support the adoption of renewables, and improve system resilience. Both agencies stress that digital transformation is essential for achieving net-zero goals and building a sustainable, future-ready energy system.

From a digital technology perspective, the energy sector is facing a decision point whereby it needs to decide how it will move forward. Standing still is no longer an option. The sector needs guidance and independent expertise to navigate the challenges ahead and to identify the most appropriate solutions that will deliver impact, with confidence to adopt and deploy to not just one asset, but to scale across their respective organisations to maximise the return.

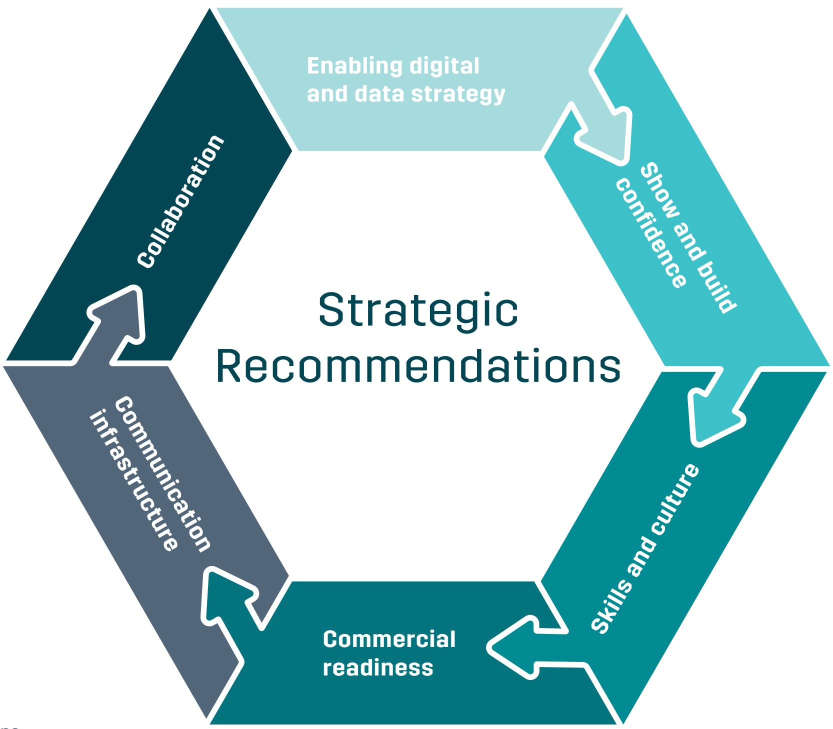

Figure 1 - Strategic Recommendations

[2] UK Gov (2021), 'Digitalising our energy system for net zero: strategy and action plan'
[3] IEA (2023), 'Digitalisation'
[4] IMO (2025), 'IMO to develop global strategy for maritime digitalisation'

Enabling digital and data strategy	Digital strategy	Closely intertwined with compelling business cases, the adoption of digital technologies should be guided by a comprehensive and well-thought-out digital strategy. It should prioritise areas where digital tools can offer maximum impact. Moreover, the strategy should include clear objectives, timelines, and indicators for measuring success.
	Data strategy	To address various data challenges mentioned in this report, the energy sector should focus on developing and implementing effective data strategies. These strategies should optimise the use of existing data, improve data quality and management, and encourage data sharing.
	Develop supportive policies and regulations	Establish clear and consistent policies and regulatory frameworks that encourage the adoption of digital technologies while addressing concerns around data security and privacy. This is particularly important for emerging areas like hydrogen and CCUS to provide a stable investment environment.

Show and build confidence	Life like test and demonstration environments	With limited budgets and a necessity to ensure digital technology investments deliver impact to operations and provide ROI, the UK energy industry needs a purpose-built test and assurance facility to emulate real-world industrial settings. This will allow digital technology to be safely showcased and demonstrated, reducing investment risks, boosting confidence, and enhancing adoption levels.
	Promote hubs and pilot projects	Support the establishment and expansion of digital hubs focused on the energy sector to enable collaboration, knowledge transfer, and the testing and assurance of new digital solutions. Funding of pilot projects and demonstrators showcase the benefits and feasibility of these technologies in real-world settings.
	Case studies	To establish confidence in digital technology and its history of real-world applications, a readily accessible and searchable repository of case studies should be created. These case studies should offer a detailed overview of the technology, deployment location(s), participating companies, findings, and the associated return on investment (ROI).
	Digital technology for ageing assets	For every energy asset type, regardless of age, complexity or planned Cessation of Production (CoP) dates, there are many low-cost, high-impact technologies that can be easily deployed and scaled. The energy industry supply chain should be supported to identify, evaluate, deploy and adopt these into their operations.

Skills and culture	Invest in skills development	Implement targeted programs to upskill the existing workforce and train new professionals in digital technologies relevant to the sector. This includes fostering collaborations between educational institutions and industry to develop specialised training courses and apprenticeships, delivering skills in context with industry challenges.
	Workforce training and change management	Digital adoption in the energy sector requires a skilled and engaged workforce. Continuous training and fostering a culture of change are essential. These should be part of a change management programme that considers the broader impact of digital technology adoption. With numerous stakeholders and service providers involved, the industry needs an advisory service to navigate this complex landscape.
	Cultural operational philosophy	Culture is key to adopting digital technology. An open and innovative culture helps organisations embrace change, support new ideas, and encourage learning while aligning efforts with organisational goals set by the executive team.

Commercial readiness	A case for investment	To secure investment in the adoption of digital technologies, compelling business cases that are value-driven, address real problems, and align with strategic goals are essential. Whether a digital provider is presenting their solution or an energy operator is seeking internal funding, the advantages of the digital technology must be explicitly articulated so that decision-makers can justify investment.
	Improved commercial environment	To promote digital technology adoption in the supply chain, commercial models must evolve. Reviewing and adapting current models to meet the energy industry's needs is essential. Incentives should encourage digital technology use, even if it impacts traditional revenue models. Performance-based contracts and subscription services, aimed at enhancing reliability and efficiency, are potential solutions.

Communication infrastructure	Enhancing connectivity	Digital technologies require reliable connectivity. Government and energy operators need to invest in robust networks and data architecture. The energy supply chain should also prioritise adoption of technologies that operate in low bandwidth or adaptive bandwidth environments.
	Address cybersecurity concerns	Implement robust cybersecurity measures and frameworks to protect digital infrastructure and data within the energy sector, building trust and ensuring the secure adoption of advanced technologies.
Collaboration	Foster collaboration and data sharing	Encourage greater collaboration across the energy sector, including between operators, technology providers, research institutions, and government bodies, to facilitate knowledge sharing and the development of common data standards and platforms.
	Energy sector collaboration	Mechanisms are required to facilitate collaboration within the energy industry. This helps in improving digital adoption by promoting shared expertise, learnings and resources, enhancing operational efficiency, reducing cost, accelerating innovation, and supporting sustainability objectives.
	Cross-sectoral collaboration	Encouraging and supporting collaboration across sectors helps ensure a unified and effective energy transition. This kind of collaboration facilitates cross-sector learning and knowledge exchange, leading to the creation of new markets, platforms, and opportunities that can be employed within the energy network.

Table 1 - Strategic Recommendations

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Introduction

With a global drive to a Net Zero future, countries and companies worldwide are developing their decarbonisation strategies with the growing recognition that digital technologies are a key ingredient necessary for the success of their plans. This importance was summarised in impactful remarks made by Axel van Trotsenburg (Senior Managing Director, World Bank Group) at the Global Digital Summit in 2024, who stated[5]:

Against this backdrop, it's helpful to consider the wider UK landscape of digitalisation and digital adoption before focusing on the UK Energy Industry's placement and performance.

The UK

On the world stage, the UK features in the top third of the 2024 International Institute for Management Development (IMD) World Digital Competitiveness Ranking[6], as the 18th most competitive out of 67 World Competitiveness Yearbook countries. Whilst encouraging, the UK is not a top performer. Two other G7 countries, Canada and the USA, are significantly ahead with other European countries also featuring higher. In the 2024 IMD Future Readiness breakdown, which is the level of country preparedness to exploit digital transformation, the UK slips from 18th to 25th in the rankings. If the UK is to succeed in its global digital competitiveness, then we need to do better, and digital adoption is a key determinant of our future success.

Indeed, the importance of digital adoption has been recognised by successive UK governments through the formation and continuation of a Digital Adoption Taskforce[7],[8]. Although the adoption challenge applies across many industries, the inherently risk-averse energy industry faces particular challenges, which are explored in this report.

Within the UK, the emphasis on digital adoption is also echoed by the Artificial Intelligence Action Plan[9] which will consider how the UK can adopt artificial intelligence to enhance growth and productivity.

The UK Energy Industry

As stated by the Digital Catapult , the energy industry is experiencing a significant transition towards decentralisation, decarbonisation and digitisation. This transition is providing new opportunities and challenges for investment and growth for both domestic and international players and digital is already playing a leading role. Together with clean energy industries, the UK Government recognises digital technology as one of the eight growth-driving sectors recognised by the UK Government as part of its Invest 2035 report[11].

Emphasising this growth potential while highlighting the pivotal role of digital adoption, a study by the World Economic Forum in conjunction with Accenture found that digital solutions could reduce 2020 global emissions by up to 20% by 2050 and can already reduce emissions by 4-10% by 2030 by accelerating the adoption of digital technologies[12]. The report emphasised that, to do this, there must be improved digital skills, data transparency and accelerated technology adoption.

The UK energy industry is focused on the role digitalisation plays in delivering the UK's Net Zero's ambitions with awareness of both the opportunities and barriers associated with improving levels of digitalisation and digital adoption. A recent reflection of this can be found in the Offshore Energy Data & Digital Maturity Survey[13], which surveyed a cross section of the UK energy industry, including renewable energy companies, in 2023. The report emphasised the crucial role of digitalisation for achieving Net Zero and highlighted modest digital maturity improvement of 8% since the last survey in 2020. While this hints at small advances in digital technology adoption, the report clearly identified multiple barriers impeding both digitalisation and digital adoption.

> **"Embracing digitalisation is no longer a choice, it is a necessity."**

[5] World Bank Group (2024), 'Remarks by Axel van Trotsenburg, Senior Managing Director, at the Global Digital Summit'
[6] Institute for Management Development (IMD) (2024), 'IMD World Digital Competitiveness Ranking 2024'
[7] Comms Council UK (2024), 'Summary of 2024 Autumn Budget'
[8] DBT (2024), 'Membership of the SME Digital Adoption Taskforce Announced'
[9] DSIT (2024), 'Artificial Intelligence (AI) Opportunities Action Plan: terms of reference'
[10] Catapult Digital (2024), 'Digital Solutions for the Energy Sector'
[11] DBT (2024), 'Invest 2035: the UK's modern industrial strategy'
[12] World Economic Forum (2022), 'Digital solutions can reduce global emissions by up to 20%. Here's how'
[13] OEUK (2023), 'Offshore Energy Data & Digital Maturity Survey'

6. Scope, objectives and report structure

In the wider context, the purpose of the report is to provide an international benchmark and comparative analysis of digital technology adoption within the UK energy sector. The report aims to measure the UK's progress against global leaders, identify key gaps (such as culture, regulation, and technology), and recommend strategies to enhance the UK's competitiveness.

The report focuses on five major areas that mirror the structure of the main body of the document. These are detailed below:

UK Energy Industry Benchmark

Evaluating the current levels of digital technology adoption in international energy sectors and comparing them with UK operations. The detailed scoring and analysis for each of the digital technologies by energy sector summarised in this section can be found in Appendix A.

International Comparison/ Benchmark

Highlighting notable best practices from top-performing countries or industries in digital technology adoption, focusing on operational efficiency, productivity, cost savings, safety improvements, and sustainability goals. The detailed analysis of individual country performance compared to the UK, summarised in this section, can be found in Appendix B.

UK Cross-Sector Comparison/Benchmark

Providing a summary view of digital adoption levels within the UK energy sector compared to other sectors like aerospace, automotive, manufacturing, pharma, and finance. The detailed analysis of individual sector performance compared to the UK energy sector, summarised in this section, can be found in Appendix A.

Gap Analysis (UK strengths/weaknesses)

Identifying gaps between the UK energy industry and international benchmarks, including digital infrastructure, investment in digital technologies, workforce readiness, and adoption of relevant digital technologies.

UK Barriers to Adoption

Analysing the major barriers impeding the UK's progress in the adoption of digital technologies.

Methodology

The research carried out in this report followed a stage-based approach, detailed below:

7. Report Structuring

With wide scope coverage, the report was structured to simplify the presentation of analyses while also organising the content to clarify the linkage between each energy sector, the energy lifecycle and digital technologies. Key steps are outlined below:

- Determination of the energy sectors to be reflected in the report - see Section 12
- Determination of the digital technologies to be reflected in the report - see Section 14
- For every sector, analysis of the production, storage, transmission/distribution, and utilisation aspects of that sector's lifecycle
- Separate analysis of grid/electrical storage and energy efficiency
- Detailed scoring and analysis for each digital technology by energy sector is in Appendix A.
- The detailed scoring and analysis of individual country performance compared to the UK, summarised in Section.

8. Desk based research

The extensive research exercise can be summarised as follows:

- **Industry and Internal Reports:** Reports and studies from organisations such as the Institute for Management Development (IMD), the International Energy Agency (IEA), and the Energy Transition Institute (ETI), along with proprietary internal studies, provided structured insights into digital maturity levels and use cases across the sector.
- **Government and Policy Papers:** UK and Scottish Government publications and strategic roadmaps helped identify regulatory drivers and public sector support for technology deployment.
- **Media Coverage and Public Sentiment:** Online media, news articles and press releases were reviewed to understand public perception relating to each technology.
- **Online Activity and Signals:** Public digital signals, including trends in Google Search activity and professional discourse on LinkedIn, were used as proxies for interest and workforce engagement with each technology.

9. Scoring Framework

With no recognised scoring framework for evaluating digital adoption levels, a custom model was developed. While subjective and reflective of the authors analysis and interpretation, a scoring framework is integral to ensure a consistent and repeatable method of evaluating the levels of digital adoption detailed in this report.

The level of adoption of each digital technology was scored using the framework below:

Scoring was informed by a combination of literature reviews and analysis of published and private literature, survey results and consultation with internal NZTC SMEs.

1. **No Adoption:** The technology is not used or has negligible presence.
2. **Initial Exploration:** Pilot projects or minimal use exist, but adoption is not widespread.
3. **Early Adoption:** Limited deployment in specific applications, with some operational impact.
4. **Moderate Adoption:** Technology is used in several areas, with noticeable benefits, but not fully integrated.
5. **Significant Adoption:** Widespread use with substantial operational impact, though not universal.
6. **High Adoption:** Near-complete integration across most relevant applications, with mature implementation.
7. **Complete Adoption:** Fully embedded across all applicable areas, representing industry-leading practice.

Figure 2 - Scoring framework

10. Analysis and reporting

The penultimate stage involved the detailed analysis of the content collected in the previous stage. The analysis identified major themes, trends, and patterns that were documented in the report structure with definitions of the energy sectors and technologies discussed in this report also provided. Key steps are outlined below:

- Define the energy sectors and technologies
- Assess the levels of adoption of digital technology for each sector and its lifecycle
- Analyse the UK performance in digital adoption, recording gaps
- Analyse the relative levels of adoption across the sectors e.g. which sectors are leading
- Analyse the relative levels of adoption of specific digital technologies e.g. which technologies are leading
- Assess UK non-energy learnings and findings
- Assess international (energy and non-energy) findings

Overall, the analysis informed the scoring assessment, conclusions and recommendations outlined in Sections 12-16.

11. Assessment, conclusion and recommendations

The final stage utilised the analysis conducted previously to provide the foundation for a thorough assessment of the digital adoption levels across industries and geographies. For the digital technologies identified, a custom scoring model was developed (see Section 9) and scoring was conducted for their level of adoption in the UK energy industry.

The comprehensive analysis, evaluation, and scoring facilitated the development of the report's conclusions and recommendations.

UK Energy Industry Benchmark

An extensive literature review was undertaken to provide the evidence and justification for the scoring and analyses contained in Appendix A. Whilst subjective and reflective of the views of the authors, the analysis highlights the perceived levels of adoption across the selected energy sectors within the UK. Should further detail and industry verification be needed, industry surveys and detailed information gathering would be expected.

For clarity, the report considers:

Fossil fuels
Primarily oil and gas, but also considering biomass plant

Nuclear
Arge-scale nuclear power plant

Wind
Onshore and offshore industrial-scale wind turbines (i.e. not domestic)

Wave/Tidal/Hydro
A generalised view of wave, tidal and hydro power

Hydrogen
Industrial applications where hydrogen is the dominant fuel

Solar
Industrial-scale solar farms

Geothermal
Heat from industrial-scale geothermal resources

CCUS
Industrial-scale carbon capture, utilisation and storage facilities

Electrical network
Consideration of the wider energy network that will include energy storage and transmission.

The analysis compared the application areas of each technology within the sectors, including production, storage, and transport of energy carriers like oil, gas, and hydrogen, as well as the resulting electrical production and network transmission and storage.

For each energy area, specific digital technologies were evaluated. These were:

Artificial Intelligence
The applications of machine learning and advanced pattern recognition, predictive analytics, large language models (LLMs) and generative AI

Digital Twins
The use of simulation and modelling, whether directly connected to a physical asset or stand-alone, or a digital copy, used to infer potential responses and behaviours of real or potential industrial assets

Remote operations
The connection from an operating asset to a remote location to enable monitoring, diagnostics, and levels of interaction, including control.

Robotics and autonomous systems
The deployment and operation of robotics (controlled, semi-autonomous and fully autonomous) to perform operations that provide productivity gains, operational efficiency, and remove risks to human operators.

Cybersecurity
The systems implemented to provide secure operations, to prevent interruption and disruption to IT systems, either from internal or, more often, external sources such as viruses and malicious attacks from 3rd party organisations.

Key findings and observations are presented in the following sections.

12. Adoption levels by Energy Sector

All sectors were scored according to the framework outlined in Section 9. The figure below shows the overall average score for each.

The leading sector for the adoption of digital technology is the electrical network; however, in this sector, deployment of robotics is still in a period of growth. As anticipated, the fossil fuels and nuclear sectors are quite mature, but both wind and solar show higher levels of adoption in some areas. The averaging of scores across the application areas complicates the analysis.

In Section 13, each application area will be examined further, providing clearer comparisons between sectors. This will include an assessment of how effectively digital technologies are being implemented in the production, storage, and transportation of energy carriers (the fuel), as well as in the generation of electricity.

The digital technology adoption levels are generally low in geothermal, hydrogen, and CCUS, except for cybersecurity. This corresponds with the low volume of deployed assets in the UK, especially for CCUS and Geothermal.

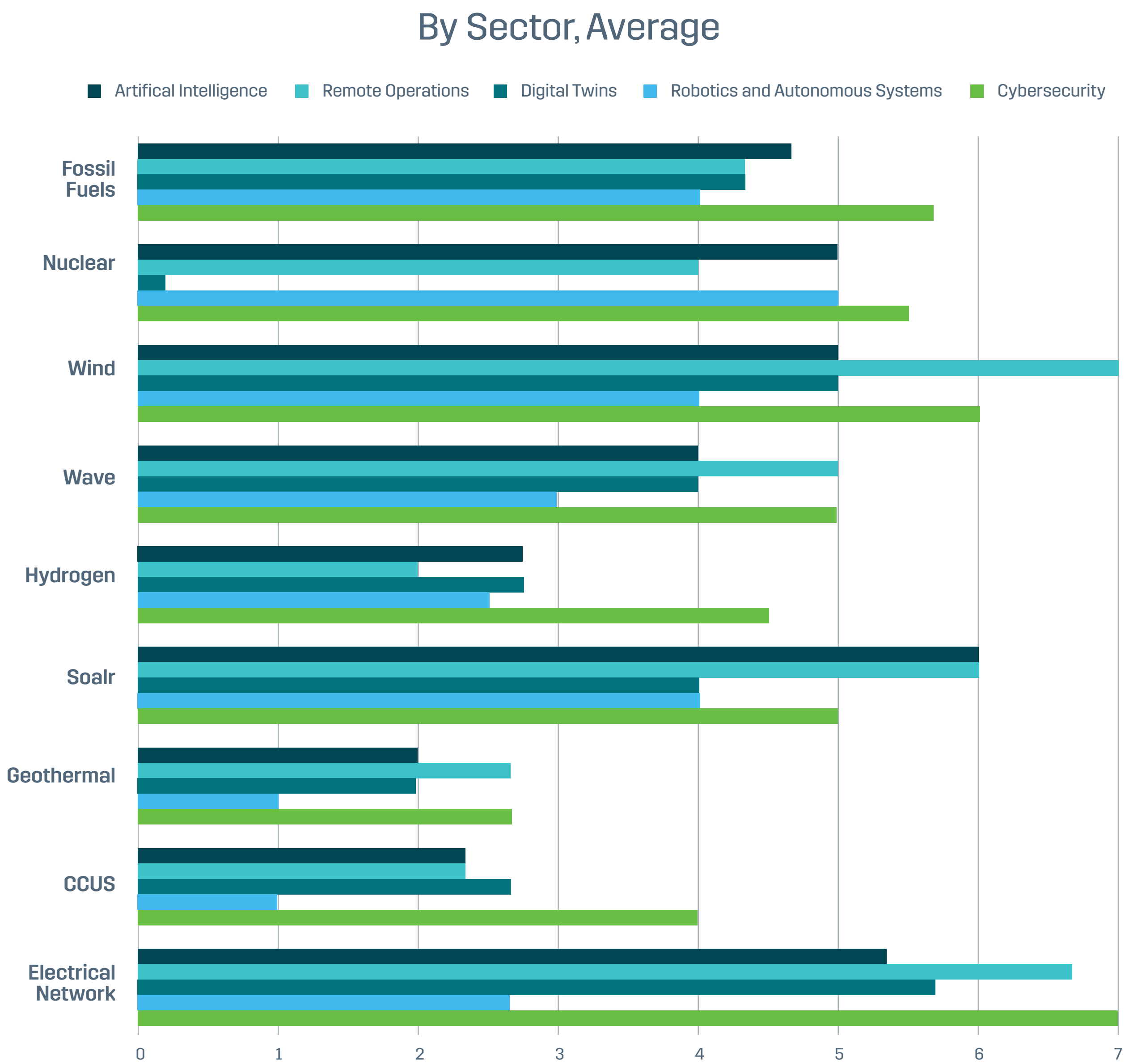

Figure 3 - UK Energy Sector Adoption Comparison

In Figures below, the comparison across sectors demonstrates the maturity of solar and wind energy for electrical production, similarly low levels of adoption for CCUS and geothermal energy, with relatively high maturity in fossil fuels and nuclear energy. More advanced levels of adoption can be seen for the electrical network, with a noticeable difference in adoption levels for robotics and autonomous systems.

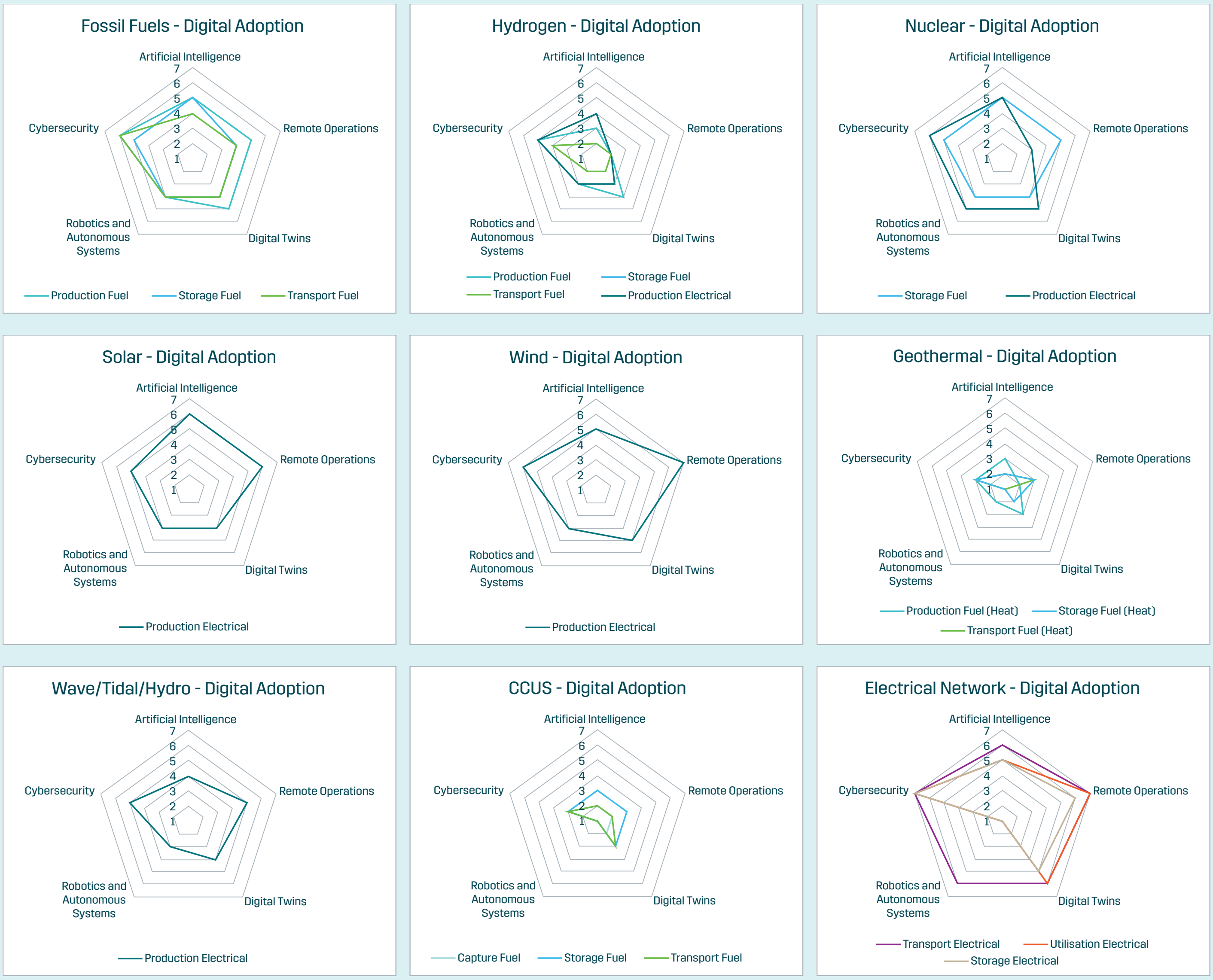

Figure 4 - UK Energy Sector Adoption Side-by-Side Comparison, by Sector

Appendix A provides more detailed narrative relating to each of the images presented above.

13. Adoption levels by Application

The areas of application for digital technologies are not the same for all sectors. Comparison between sectors is needed to identify where learning opportunities may arise.

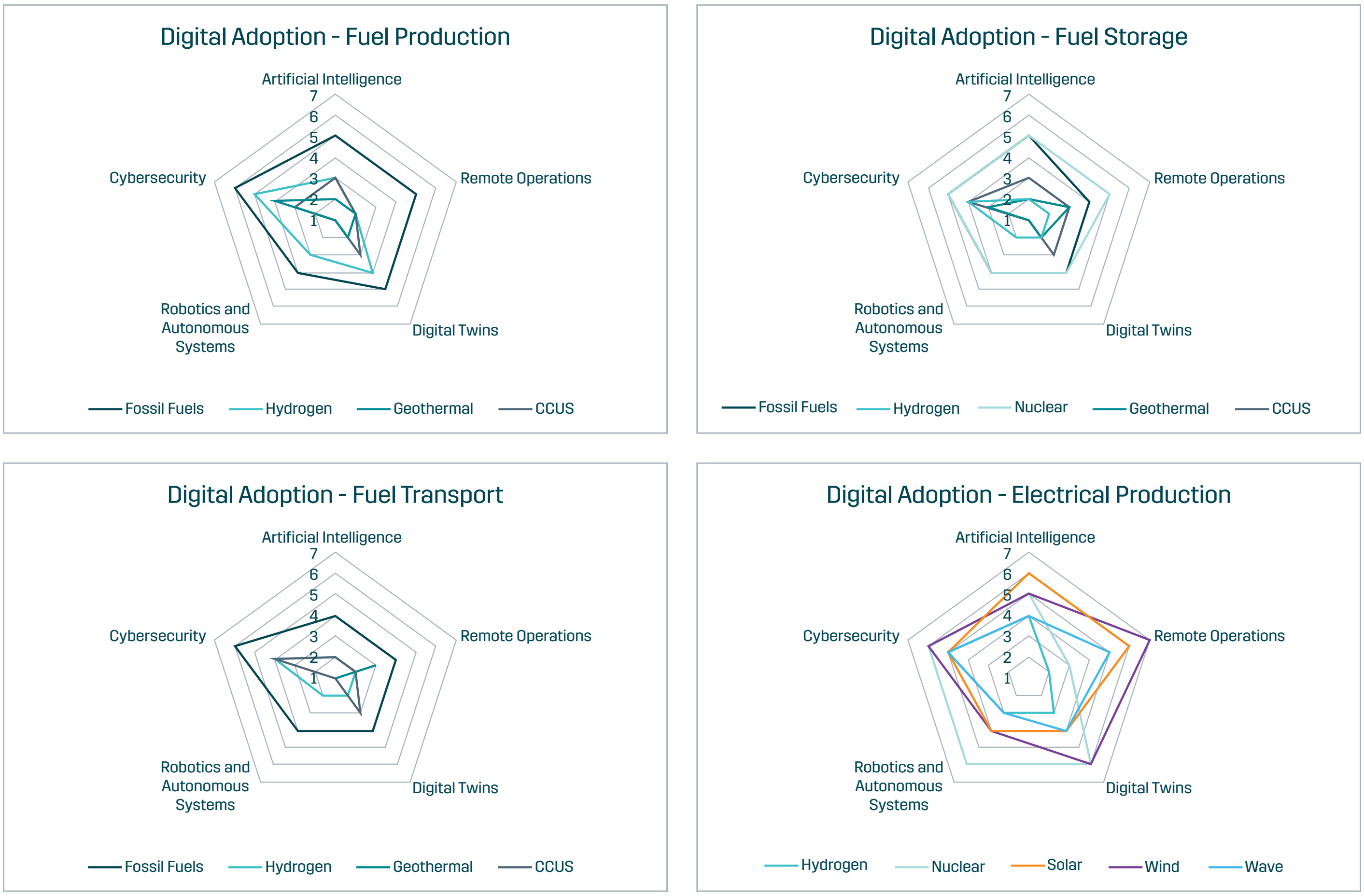

Figure 5 - UK Energy Sector Adoption Side-by-Side Comparison by Application

Observations are summarised below:

- **Fuel production:** the leading sector is fossil fuels (predominantly oil/gas), given the adoption of digital technologies over many years. What is important to note, however, is that whilst the adoption may be viewed as relatively high, this is driven by recognition of localised best practice rather than an industry-wide level of adoption. The risk-averse, safety-focused nature of the industry is not conducive to the implementation of new technologies without significant testing and qualification.
- **Fuel storage:** the leading sectors are fossil fuels and nuclear. Again, not unexpected, highlighting the opportunity for shared learning between sectors and to build on the experience of others rather than reinvention.
- **Fuel transportation:** fossil fuels sector leads the way with the adoption of digital technology for fuel transportation. Again, not a surprise given the extent of pipelines that have been deployed, and continue to be maintained, within the UKCS.
- **Electrical production:** the deployment and adoption of digital technologies from hydrogen, nuclear, solar, wind and wave/tidal/hydro raises some interesting observations. Largely focussed on operations and maintenance of assets, the leading sector is nuclear (unsurprising given the critical nature of the power plant). Solar has a high adoption rate of AI and both solar and wind lead with remote operations adoption. Wave/tidal/hydro is generally lower in adoption rates with hydrogen at the lowest.

These observations correlate with the maturity of the nuclear, solar and wind assets and the relative immaturity of others.

14. Adoption levels by Digital Technology Type

Within this section analysis is presented for each digital technology, to visualise the pattern of adoption across all sectors and application areas. Whilst a more detailed and more complex analysis, the visualisations provide a complimentary view, and additional insights compared to Sections 12 and 13 above.

Artificial Intelligence

Applications of artificial intelligence are in their infancy for CCUS, geothermal and hydrogen technologies, with higher levels of adoption in solar, electrical networks, fossil fuels and nuclear. The volume of deployed assets has a direct correlation to levels of AI adoption.

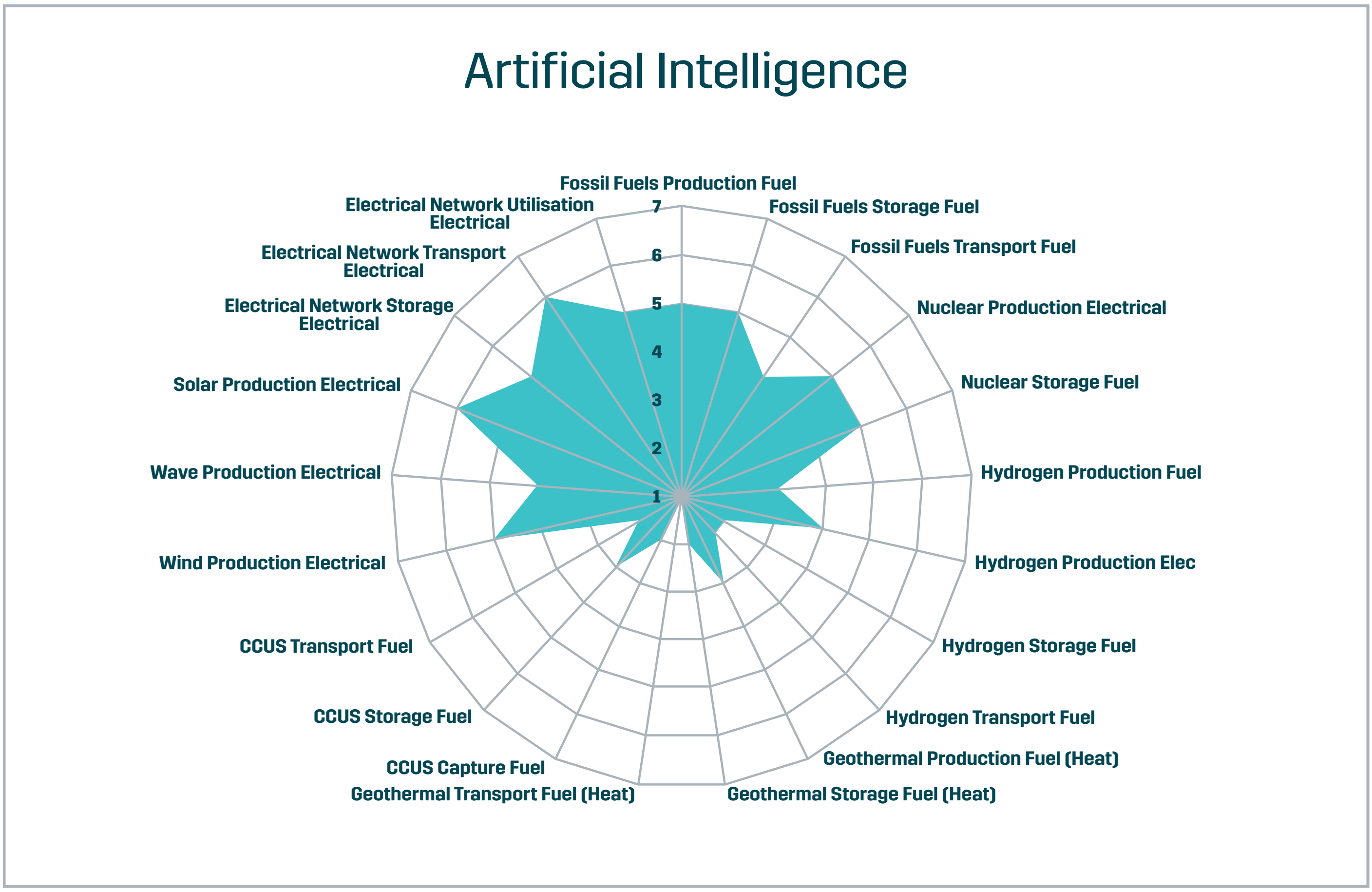

Figure 6 - Artificial Intelligence - UK Energy Sector Adoption Comparison

Remote Operations

From the figure below, adoption of remote operations is noticeably higher within the electrical networks, solar, wave and wind sectors, with fossil fuels (production) and nuclear fuel storage appearing as medium level of adoption.

This is in line with expectations given the large, unmanned assets that exist for these sectors. For fossil fuels, the increasing interest in remove personal-on-board (PoB) and transitioning to remote monitoring and operation is driving a short towards remote operations.

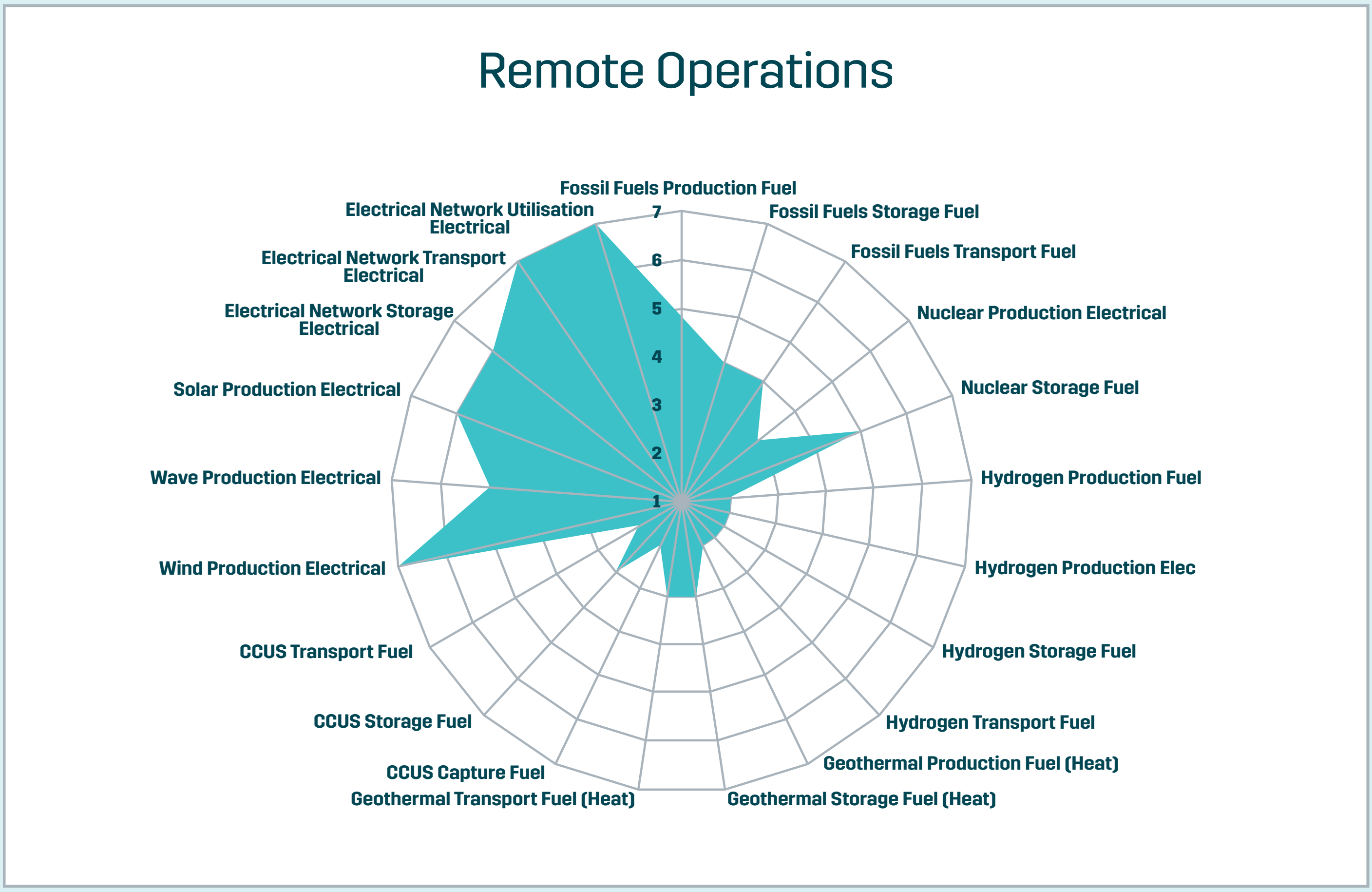

Figure 7 - Remote Operations - UK Energy Sector Adoption Comparison

Digital Twins

When considering digital twins, the terminology and classification within the context of this report are broad and include simulation and modelling of physical assets. It is not constrained to physically connected digital twins that synchronise with real physical asset operation.

The figure below highlights, a higher level of adoption within the established energy sectors (electrical network, nuclear, wind, fossil fuel production). For CCUS, geothermal and hydrogen, the opportunity exists to influence new designs based on digital models.

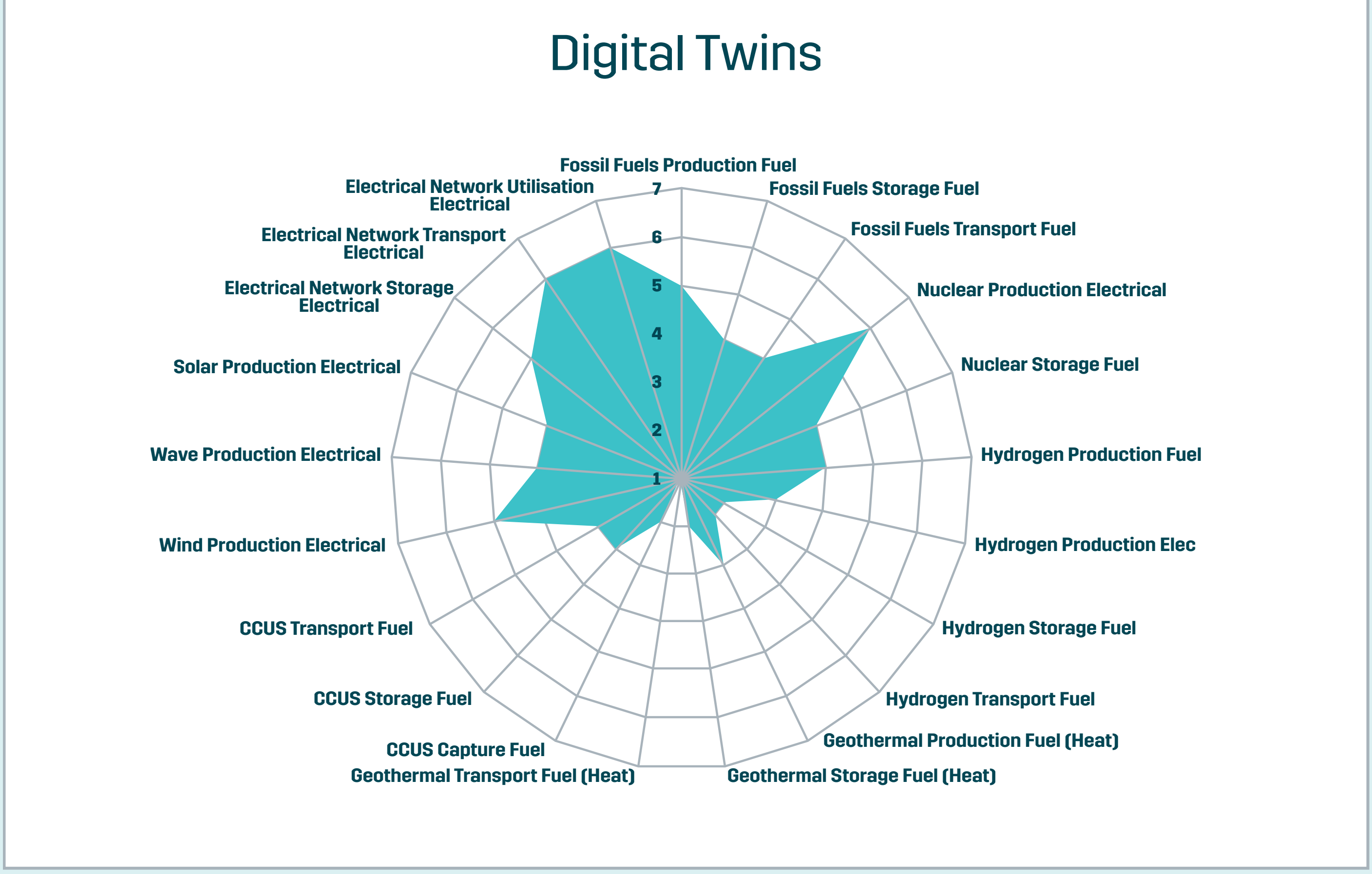

Figure 8 - Digital Twins - UK Energy Sector Adoption Comparison

Robotics and Autonomous Systems

The UK has the least advanced robotics sector in the G7[14]. In an ONS 2023 survey looking at adoption of technology, robotics had an adoption rate of 4% in 2023 and a planned adoption rate of 5% in 2024[15]. Of the digital technologies considered, robotics had the lowest adoption rate. This is expected as the resilience of robotics and suitability for operation in offshore conditions is known to be a challenge.

The electrical network frequently adopts drones for site and powerline inspections, as well as wider area safety assessments. In nuclear operations and maintenance, robotics are regularly used for inspections.

In almost all other areas the levels of adoption are low, even in fossil fuels (predominantly oil/gas). Whilst there are land, sea and air devices used, the levels of adoption across the industry are at a medium level. The appetite is there, but technology maturity is a challenge.

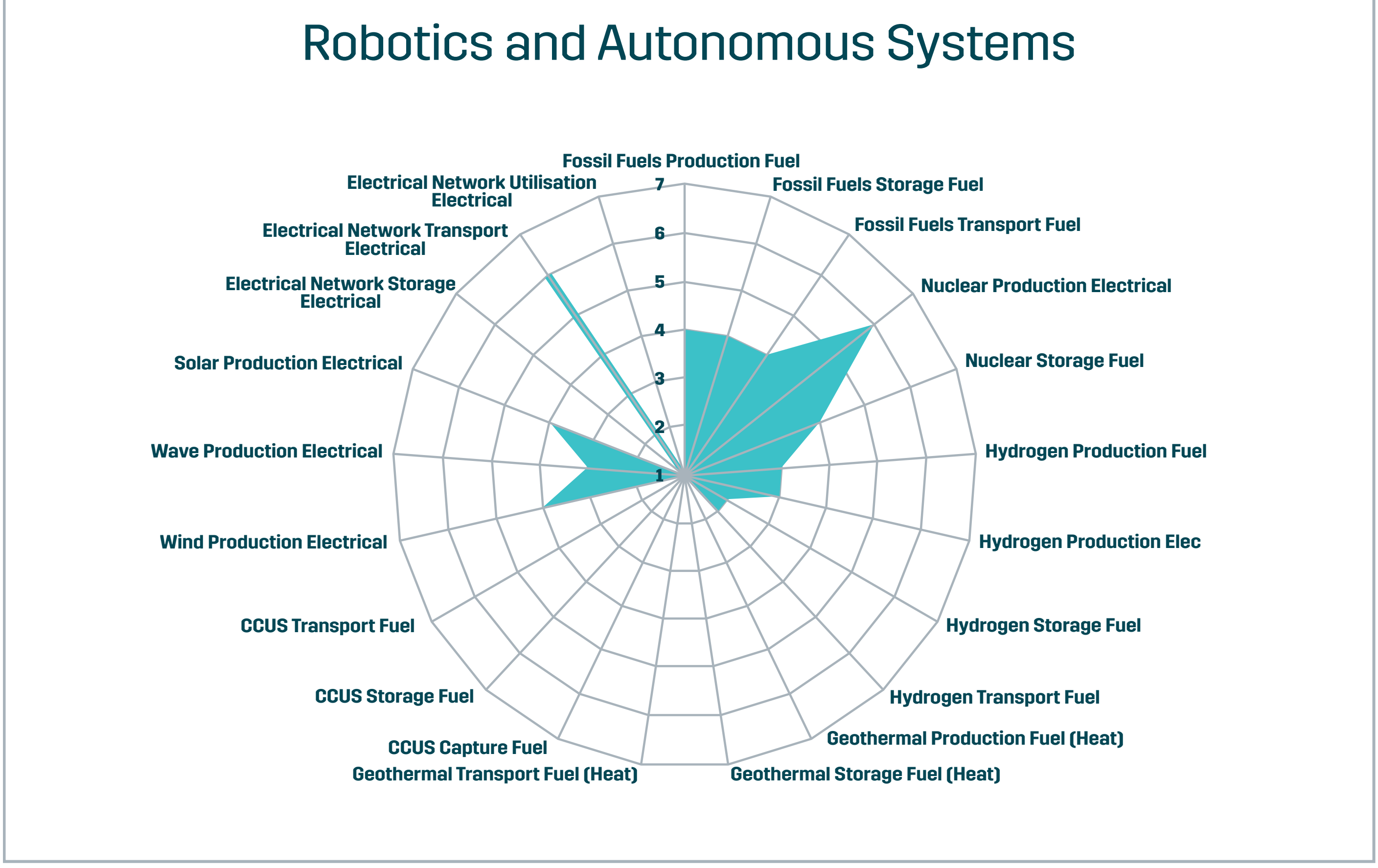

Figure 9 - Robotics and Autonomous Systems - UK Energy Sector Adoption Comparison

[14] Tony Blair Institute (2024), 'A New National Purpose: The UK's Opportunity to Lead in Next-Wave Robotics'

[15] ONS (2023), 'Management practices and the adoption of technology and artificial intelligence in UK firms: 2023

Cybersecurity

Operators within the energy sector, including oil and gas producers, are legally required to ensure high cybersecurity standards under the Network and Information Systems (NIS) Regulations[16]. Also, the UK government is further strengthening the regulatory landscape with the Cyber Security and Resilience Bill[17], aimed at enhancing the cybersecurity of critical national infrastructure, including the energy sector. Cybersecurity provision is a requirement.

The energy sector's increasing reliance on digital systems provides more opportunities for hackers and successful attacks can cause widespread economic and social consequences. With over 50% of UK businesses experiencing a cyber breach or attack in the past year, over 75% consider cybersecurity their top priority. The energy sector is the UK's top target for cyber-attacks, accounting for 24% of all attacks in 2024[18].

The UK National Cyber Security Centre[19] provides guidelines and support to protect critical infrastructure but, despite regulations, 52% of UK IT leaders do not believe the government can protect its citizens and organisations from cyberwarfare making it imperative that UK organisations stay one step ahead of threats.[20]

The figure below confirms the expected high levels of adoption in comparison to other digital technologies. For less mature sectors (hydrogen, CCUS and geothermal) adoption is driven by the low levels of assets in operation within the UK.

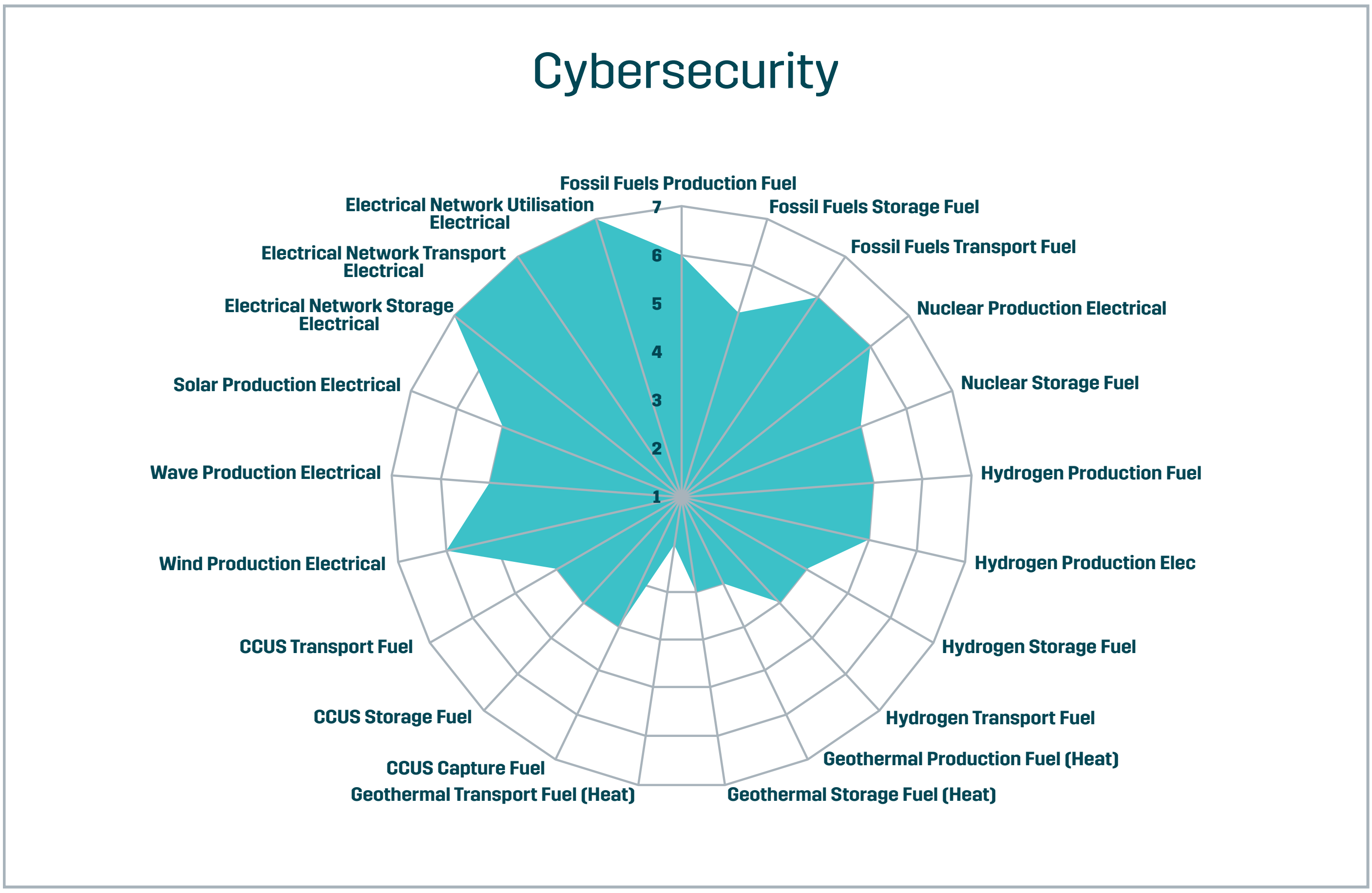

Figure 10 - Cybersecurity - UK Energy Sector Adoption Comparison

[16] UK Gov (2018), 'The NIS Regulations 2018'
[17] UK Gov (2024), 'Cyber Security and Resilience Bill'
[18] RenewableUK (2025), 'Growing cyber security threats in the energy sector and how businesses stay resilient'
[19] National Cyber Security Centre
[20] Resilience Forward (2025), 'The UK's cybersecurity landscape: key trends and challenges for 2025'

15. Key Findings and Insights

The analysis indicates that digital adoption in the UK energy sector is progressing at varying paces across different sectors and technologies:

- AI has a higher level of adoption in wind, solar, electrical networks and elements of the fossils fuels and nuclear sectors - primarily supporting operations and maintenance, forecasting and grid management
- Remote operations are leading within the electrical networks, and largely autonomous operations such as solar and wind. Fossil fuels applications are moving towards remote operations in some areas but are not a widespread adoption.
- Digital twins (including simulation and modelling) are largely utilised within the electrical network and electrical production in fossil fuels and nuclear facilities predominantly. Other areas are less mature.
- Robotics and autonomous systems are still relatively immature, seeing low levels of adoption. With some recognised applications in electrical transmission inspections, solar and wind inspections, nuclear facilities and fossil fuel applications, the low levels of adoption are as a result of low reliability of the devices.
- Hydrogen, CCUS, geothermal, and wave/tidal/hydro have a low level of adoption primarily due to the low levels of asset deployment within the UK
- Cybersecurity is a critical priority across all sectors, reflecting the understanding of the potential risks associated with increased digitalisation.

Several factors influence the adoption of digital technologies. The maturity and scale of the energy sector play a significant role, with established sectors like oil and gas having a longer history of technology integration. Regulatory frameworks, such as the NIS Directive, are driving the adoption of cybersecurity measures.

16. Recommendations

To further accelerate digital transformation in the UK energy sector, several recommendations are made.

- Energy companies must develop digital strategies aligned with their operational needs.
- Strategic investments in key digital technologies, coupled with robust data management and cybersecurity practices, are essential.
- Policymakers can play a role by providing policies and funding that encourage adoption.
- Addressing skills gaps through training and education programs, in context with industry challenges, will be vital for successful digital adoption.
- Technology providers should focus on developing interoperable and scalable solutions that cater to the specific requirements of the UK energy sector, while investors should recognise the significant opportunities presented by the digitalisation of this critical industry.

Digital technologies are crucial in transforming the UK energy sector, enhancing efficiency, sustainability, resilience, and security. Adoption levels vary. Continued investment, collaboration, and innovation are needed to achieve the UK's energy goals and a sustainable future, and the necessary digital transformation of the energy sector is vital for reaching net-zero ambitions and securing an affordable energy supply.

The risk is that legacy understanding of digital technologies prevails and is transferred into the new, arising energy spaces.

The opportunity exists for new energy solutions learn from the past, recognise the benefits that can be achieved, and seek more modern solutions rather than a direct "copy-and-paste" from fossil fuels and nuclear.

UK Cross-Sector Comparison/Benchmark

To comprehensively assess the progress of digital transformation within the UK energy sector, it is pertinent to undertake a high-level comparison with other industries. This analysis will examine the extent of digital technology adoption across key sectors, such as finance, which has effectively integrated advanced technologies, including artificial intelligence, robotics, and digital twins. The insights derived from this examination aim to inform strategic approaches to fostering innovation and accelerating digitalisation within the energy sector.

17. Finance

The finance sector in the UK is highly advanced in digital adoption compared to the energy sector. This high level of adoption can be attributed to several key factors:

Innovation and Competitiveness

The finance industry operates in a fast-paced and highly competitive environment, where innovation is crucial to staying ahead. Adopting digital technologies such as AI/ML and robotics enables financial institutions to streamline operations, reduce costs, and offer unique and personalised services, fostering a competitive edge.

Consumer Demand

As consumers increasingly demand accessible and convenient financial services, the sector has responded by integrating technologies like online banking, virtual advisory services, and remote operations. These advancements cater to the expectations of tech-savvy customers, enhancing user experience and loyalty.

Regulatory Frameworks

Supportive regulations have played a significant role in encouraging digitalisation within finance. Clear cybersecurity, data protection, and innovation guidelines have helped institutions adopt advanced technologies without compromising security or compliance.

Risk Management Necessities

In an industry where managing financial risks is paramount, technologies such as AI and digital twins provide unparalleled capabilities in fraud detection, market prediction, and strategic planning. These tools help mitigate risks and optimise decision-making processes.

Global Integration

The finance sector is deeply integrated into the global economy, requiring technologies that facilitate seamless international transactions, compliance, and communication. Digital tools ensure efficiency and security in these processes, further driving adoption.

These factors collectively establish the finance sector as a leader in digital innovation, setting a benchmark for other industries, including the energy sector.

AI/ML

AI and ML are widely used in the finance sector for fraud detection, risk management, and personalised customer services. These technologies help in improving decision-making, enhancing customer experience, and reducing operational costs[21].

Remote Operations

Remote operations in finance include online banking, remote customer support, and virtual financial advisory services. These technologies enable financial institutions to provide services to customers anytime, anywhere.

Digital Twins

Digital twins are used to simulate financial models and predict market trends. These models help in optimising investment strategies, managing risks, and improving financial planning.

Robotics

Robotics in finance focuses on the use of robotic process automation (RPA) for tasks such as data entry, transaction processing, and compliance reporting. Workflow automation enhances efficiency, accuracy, and reduces operational costs.

Cybersecurity

Cybersecurity is critical in the finance sector to protect sensitive financial data, ensure the integrity of transactions, and safeguard against cyber threats. The sector invests heavily in cybersecurity measures to protect against data breaches and fraud[22,23].

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[21] Bank of England (2024), 'Artificial Intelligence in UK financial services - 2024'
[22] UK Finance (2024), 'UK banks embrace digital transformation: fintech collaboration key to future success'
[23] FinTech Magazine (2025), 'UK Finance: AI Spend to Hit Record Levels in 2025'

18. Aerospace

The levels of adoption experienced in the UK aerospace sector have been driven by several key factors.

Operational Efficiency

The need for safety and efficiency has driven the UK aerospace sector to adopt advanced technologies. Tools like AI, digital twins, and IoT help monitor operations, predict maintenance needs, and streamline production, cutting costs and improving quality.

Investment

Significant investments from both the UK government and industry stakeholders, such as through the Aerospace Technology Institute (ATI) program[24], have accelerated adoption.

Sustainability Regulations

Strict regulatory requirements have compelled the sector to employ cutting-edge technologies to ensure compliance and maintain high standards. These drivers combine to make the aerospace sector a leader in digital innovation and transformation. Regulatory pressures have encouraged the adoption of digital tools to optimise resource use, reduce emissions, and ensure compliance with evolving standards.

Agility and Innovation

The need for flexibility and faster innovation is a key factor. Digital technologies allow companies to test ideas quickly, try new designs, and learn from failures without high costs or risks. This speeds up the development of new products and helps businesses respond efficiently to changing customer needs and regulations.

Data-as-an-asset

Recognised as a strategic asset, advanced analytics and big data capabilities are providing better decision-making, traceability, and more personalised customer offerings.

In summary, the main drivers for digital adoption in the UK aerospace sector include the pursuit of efficiency and competitiveness, the need for agility and innovation, the strategic value of data, evolving business models, sustainability imperatives, and collaborative ecosystems that foster technological advancement.

AI/ML

AI and machine learning are being implemented in the aerospace sector to enhance flight operations, optimise flight paths, and enable predictive maintenance. AI-driven systems process large amounts of data quickly, including weather and air traffic data, to suggest efficient routes, reducing delays and improving fuel consumption and range .

Remote Operations

Regularly used for unmanned aerial vehicles but also in the daily monitoring of airspace through air traffic control. London City Airport was the first major city to be controlled by a remote digital tower, located 115km away from the airport[26].

Digital Twins

Digital twins are used to create virtual replicas of aircraft and their components. These digital models help in monitoring the health of aircraft, predicting failures, and optimising maintenance schedules, thereby reducing downtime and operational costs.

Robotics

Robotics in aerospace manufacturing streamline production processes, improving precision and reducing human error. Robots are used for tasks such as assembling aircraft components, welding, and painting.

Cybersecurity

With the increasing reliance on digital technologies, cybersecurity is crucial in protecting sensitive data and ensuring the safety of flight operations. The aerospace sector invests heavily in cybersecurity measures to safeguard against cyber threats.

The aerospace sector in the UK is more advanced in its digital adoption compared to the energy sector. This is driven by the critical need for safety, operational efficiency, and cost reduction as well as the natural cascade of technologies from defence applications through to commercial aircraft. The sector has heavily invested in AI/ML for optimising flight operations and predictive maintenance, and in digital twins for real-time monitoring and predictive maintenance of aircraft. The use of UAVs for remote operations and robotics in manufacturing processes further enhances precision and reduces human error. The high adoption of cybersecurity measures ensures the protection of sensitive data and the safety of flight operations[27,28].

[24] ATI (2021), 'Digital Transformation'
[25] Forbes (2025), 'Is AI Cleared for Takeoff In The Aerospace Industry'
[26] NATS (2021), 'London City is the first major airport controlled by remote digital tower'
[27] ADS, 'Digital Transformation for Aerospace & Defence Group'
[28] ATI (2021), 'Digital Transformation'

19. Automotive

The automotive sector in the UK is also more advanced in digital adoption compared to the energy sector, with large vehicle manufacturers generally more advanced than their suppliers. Major manufacturers such as Nissan, Jaguar Land Rover, and Rolls Royce are leading the way by integrating technologies like sensors, digital twins, predictive analytics, and real-time scenario modelling into their operations, which enables them to optimise production, personalise vehicles, and offer new services such as remote vehicle-health monitoring. In contrast, many suppliers, especially SMEs, have yet to initiate significant digital pilots, largely due to barriers such as limited investment, digital skills shortages, and concerns around data sharing and cybersecurity[29].

The primary drivers for digital adoption in the sector are:

Competitiveness
The need to remain globally competitive has pushed manufacturers to embrace digitalisation, as it can deliver significant productivity gains, cost reductions, and shorter lead times.

Customer Expectations
Rising consumer demand for personalised vehicles and enhanced services has encouraged the use of digital tools that enable customisation and improved customer engagement.

Strong Leadership Engagement
Proactive engagement from C-suite executives and significant investments in digital technologies.

Innovation and Technology Trends
Advances in software, AI, and connectivity, such as the development of software-defined vehicles are reshaping the industry and driving the integration of digital technologies across the vehicle lifecycle.

Sustainability and Regulation
The push for net-zero emissions and compliance with evolving regulatory standards has made digital solutions essential for monitoring vehicle performance, supporting sustainable design, and enabling circular economy practices.

Collaboration and Ecosystem Development
Partnerships between manufacturers, technology developers, and research institutions, as well as investment in digital infrastructure and workforce upskilling, have fostered an environment that supports further digital adoption.

These drivers have accelerated digital transformation among leading manufacturers, enabling them to innovate rapidly and maintain their market position, while suppliers face greater challenges in keeping pace, resulting in a sector with varied levels of digital maturity.

AI/ML
AI and ML are revolutionising the automotive industry by enabling autonomous vehicles, enhancing manufacturing processes, and improving vehicle safety. AI is used for designing and testing vehicle components, analysing consumer data, and optimising routes to reduce fuel consumption[30].

Remote Operations
Remote operations in the automotive sector include telematics and remote diagnostics, allowing manufacturers to monitor vehicle performance and provide over-the-air updates to improve functionality and safety.

Digital Twins
Digital twins are used to simulate and test vehicle designs, optimise manufacturing processes, and predict maintenance needs. This technology helps in reducing development time and costs while improving product quality.

Robotics
Robotics are extensively used in automotive manufacturing for tasks such as welding, painting, and assembly. These robots enhance production efficiency, precision, and safety.

Cybersecurity
As vehicles become more connected, cybersecurity is essential to protect against hacking and ensure the safety of vehicle operations. The automotive sector invests in robust cybersecurity measures to safeguard data and vehicle systems[31,32].

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29 KPMG (2017), 'The digitalisation of the UK Automotive Industry'
30 The London Economic (2024), 'AI in the Automotive Industry: Advancements in Autonomous Vehicles'
31 BearingPoint (2025), 'UK Automotive Retail: Digital Sales Maturity'
32 FlowForma (2024), 'Digital Transformation in the Automotive Industry: Trends & Use Cases'

20. Manufacturing

The UK manufacturing sector demonstrates a broad spectrum of digital technology adoption, with many having embedded multiple technologies such as AI, automation, data analytics, and cloud computing into their operations. A significant portion of small to medium-sized businesses remain at the early stages of digitalisation. Larger firms and those with greater access to resources are more likely to have integrated advanced digital tools, reaping benefits like improved productivity, flexibility, and profitability. Initiatives like the Made Smarter[33] programme have accelerated SME adoption through targeted support.

The five main drivers for digital adoption in UK manufacturing are:

Productivity and Efficiency

The need to optimise operations and remain competitive has pushed manufacturers to adopt digital tools that streamline processes, improve labour efficiency, and enhance resource utilisation. The Industry 4.0 movement has been a driver for change in manufacturing.

Resilience and Agility

External drivers such as the COVID-19 pandemic and Brexit have underscored the importance of building resilient supply chains and agile production systems.

Cost Pressures

Rising energy and operational costs have made digital technologies attractive for their potential to reduce waste, improve machine utilisation, and lower OPEX.

Customer and Market Demands

Increasing expectations for quality, speed, and customisation have driven manufacturers to use data analytics and automation to deliver better products and services faster.

Sustainability and Compliance

The push for decarbonisation and regulatory compliance has encouraged the use of digital tools for monitoring emissions, improving resource efficiency, and supporting sustainable practices.

These drivers have collectively accelerated digital adoption, particularly among larger and more innovative manufacturers, resulting in measurable gains in productivity, flexibility, and competitiveness.

AI/ML

AI and ML are used in manufacturing for predictive maintenance, quality control, and optimising production processes. These technologies help in reducing downtime, improving product quality, and increasing operational efficiency[34].

Remote Operations

Remote operations in manufacturing include the use of IoT devices and sensors to monitor and control production processes remotely. This enables real-time decision-making and improves overall efficiency.

Digital Twins

Digital twins are used to create virtual models of manufacturing processes and equipment. These models help to optimise production, predict failures, and improve maintenance schedules.

Robotics

Robotics are widely used in manufacturing for tasks such as assembly, welding, and packaging, enhancing productivity, precision, and safety in manufacturing operations. Robots are also used widely within logistics and materials handling.

Cybersecurity

Cybersecurity is critical in manufacturing to protect sensitive data, intellectual property, and ensure the integrity of production processes. The sector invests in cybersecurity measures to safeguard against cyber threats[35,36].

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[33] Made Smarter programme
[34] Automation.com (2024), 'Study Shows UK Leading the AI and Machine Learning Charge for Enhanced Productivity'
[35] The Manufacturer (2025), 'Digital transformation in UK manufacturing: challenges and opportunities'
[36] ONS (2025), 'Management practices and the adoption of technology and artificial intelligence in UK firms: 2023'

21. Pharmaceuticals

The pharmaceutical sector in the UK is significantly advanced in digital adoption compared to the energy sector and exhibits a growing but uneven adoption of digital technologies, with leading companies rapidly integrating advanced tools such as artificial intelligence (AI), big data analytics, automation, and IoT into research, manufacturing, and supply chain operations. The COVID-19 pandemic acted as a major catalyst, accelerating digital transformation by highlighting the need for remote collaboration, faster drug development using AI techniques, and the development of more resilient supply chains.

Larger pharmaceutical firms and innovation hubs have embraced technologies like digital twins, blockchain for supply chain transparency, and 3D bioprinting to enhance efficiency and patient outcomes, while smaller companies face challenges related to investment, digital skills shortages, and the complexity of integrating new systems with legacy infrastructure[37].

Five key drivers for digital adoption in the UK pharmaceutical sector are:

Regulatory Pressure and Compliance

Stricter regulations and the need for transparent, auditable processes are driving companies to adopt digital solutions for data integrity, traceability, and real-time compliance monitoring.

Efficiency and Productivity

The imperative to reduce time-to-market, increase manufacturing efficiency, and cut operational costs has led to the uptake of automation, advanced analytics, and smart factory technologies.

Innovation and Competitive Advantage

The pursuit of breakthrough therapies and the need to remain globally competitive have encouraged investment in AI-driven drug discovery, digital clinical trials, and personalised medicine platforms.

Supply Chain Resilience

The pandemic exposed vulnerabilities in global supply chains, prompting the adoption of digital tools for end-to-end visibility, predictive analytics, and blockchain-based tracking to ensure continuity and quality.

Patient-Centric Care and Engagement

The shift toward more personalised, patient-focused healthcare has increased the use of digital health apps, remote monitoring, and on-call pharmacy services to improve adherence, engagement, and outcomes.

These drivers have collectively accelerated digital adoption, particularly among larger and more innovative organisations, enabling faster innovation cycles, improved compliance, and enhanced patient care. However, the sector continues to face challenges such as workforce digital skills gaps, data sharing concerns, and the need for robust standards and interoperability to fully realise the benefits of digital transformation.

AI/ML

AI and ML are transforming the pharmaceutical industry by accelerating drug discovery, optimising clinical trials, and improving manufacturing processes. These technologies help in reducing time-to-market for new therapies and improving patient outcomes[38].

Remote Operations

Remote operations in pharma include telemedicine and remote monitoring of clinical trials. These technologies enable real-time data collection and improve patient engagement and compliance.

Digital Twins

Digital twins are used to simulate biological processes and drug interactions. These models help in predicting drug efficacy and safety, optimising clinical trial designs, and reducing development costs.

Robotics

Robotics are used in pharmaceutical manufacturing for tasks such as drug formulation, packaging, and quality control. These robots enhance precision, efficiency, and safety in production processes.

Cybersecurity

Cybersecurity is essential in the pharmaceutical sector to protect sensitive patient data, intellectual property, and ensure the integrity of clinical trials and manufacturing processes. The sector invests in robust cybersecurity measures to safeguard against cyber threats[39, 40].

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[37] CPI (2025), 'The challenges with digital transformation in pharma manufacturing and how to overcome them'
[38] Whatfix (2025), 'How AI Is Reshaping Pharma: Use Cases, Challenges'
[39] Gitnux (2025), 'Digital transformation in the pharmaceutical industry statistics'
[40] CMAC, 'Digital CMC Centre for Excellence in Regulatory Science and Innovation'

22. Summary

Overall, the UK finance, aerospace, automotive, manufacturing, and pharmaceutical sectors demonstrate higher levels of digital adoption compared to the energy sector. This advancement is attributed to factors such as the need for safety and efficiency, leadership engagement, investments in digital technologies, regulatory compliance, and consumer demand for innovative solutions.

Digital adoption across the UK's major sectors varies widely, shaped by each industry's priorities and challenges. The energy sector is notable for its structured, government-led approach, focusing on technologies like smart grids and digital twins to meet net-zero goals. While this has driven strong progress among large organisations, smaller companies still face barriers such as high costs. Fragmented data affects all organisations. Conversely, sectors like finance and pharmaceuticals are driven by customer demands and rapid innovation, leading to advanced use of AI, automation, and blockchain. Manufacturing, aerospace, and automotive industries have made significant strides in IoT and digital twins to enhance operational efficiency, particularly among larger firms, though they often face uneven adoption across supply chains and regions.

Key lessons emerge from these differences. The energy sector's collaborative, policy-driven model could assist other industries, like automotive and pharmaceuticals, in overcoming supply chain fragmentation and accelerating digital adoption. However, it may also be slow to change due to established governance and standards. The customer-centric and innovation-focused strategies observed in finance and pharmaceuticals illustrate how digital adoption can deliver value when aligned with market needs.

Across all sectors, sharing best practices in upskilling, cybersecurity, and data management will be essential to ensure inclusive and effective digital transformation, strengthening the UK's competitiveness in a rapidly changing global landscape. While all sectors face common barriers such as skills shortages and cybersecurity concerns, their digital maturity varies significantly due to differing strategic priorities and operational requirements. By learning from these sectors, the UK energy sector can enhance its digital adoption, improve efficiency, reduce operational costs, and ensure regulatory compliance.

Across all sectors, sharing best practices in upskilling, cybersecurity, and data management will be essential to ensure inclusive and effective digital transformation, strengthening the UK's competitiveness in a rapidly changing global landscape.

International Comparison/Benchmark

To benchmark the United Kingdom's digital adoption within the energy sector, this section evaluates a selection of international comparators: Norway, Germany, the US, South Korea, Japan, and Singapore. These countries were chosen based on their high levels of digital maturity, their roles as significant energy producers, and their recognition for setting global standards in areas such as automation, robotics, and energy infrastructure. Although their energy systems and policy contexts vary, each offers valuable insights into the implementation and operation of digital technologies within complex industrial environments.

This section aims to identify relevant practices and highlight where and how the UK differs in its current state of digital adoption.

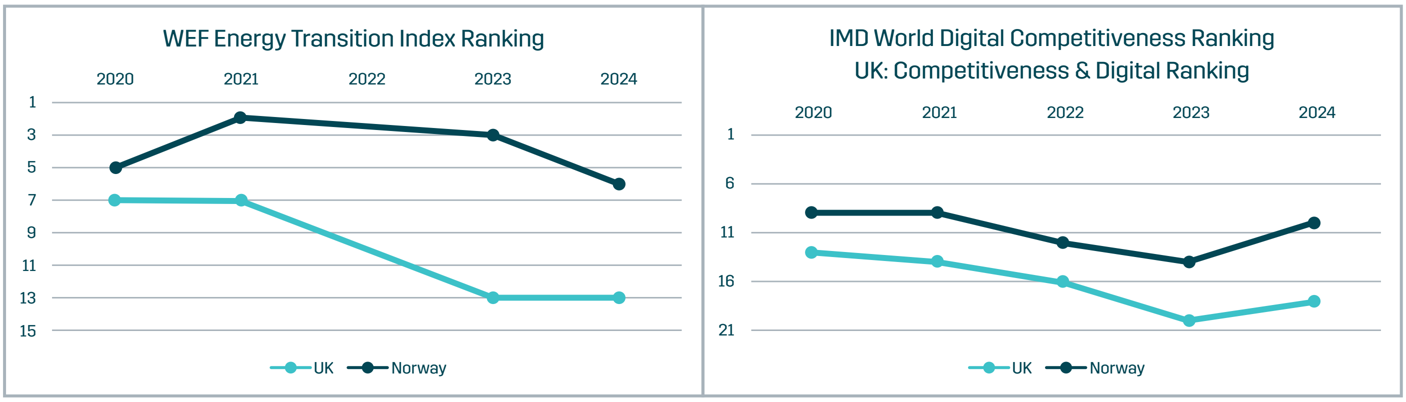
A high-level summary will be provided in the following sections, with a detailed analysis provided in Appendix B.

23. Norway

Norway demonstrates a leading example of digital integration within its offshore oil and gas sector, leveraging advanced technologies such as digital twins, AI-driven predictive maintenance, and automation across operational environments.

Platforms like the NCS DataHub facilitate open data access for performance benchmarking, maintenance, and emissions reporting. Collaboration between operators, regulators, and research institutes enables rapid scaling of innovation from R&D to operations.

Comparatively, Norway outpaces the UK in global rankings like the IMD Digital Competitiveness and WEF Energy Transition Index , reflecting its strategic execution and system-wide transformation in energy and digital sectors. It consistently scores in the top 10 of the Energy Transition Index.



(Note: WEF Energy Transition Index not published for 2022)

Figure 11 - Comparison between WEF and IMD Ranking (UK vs Norway)

While the UK excels in early innovation and policy intent, it struggles with scaling and embedding solutions into operations.

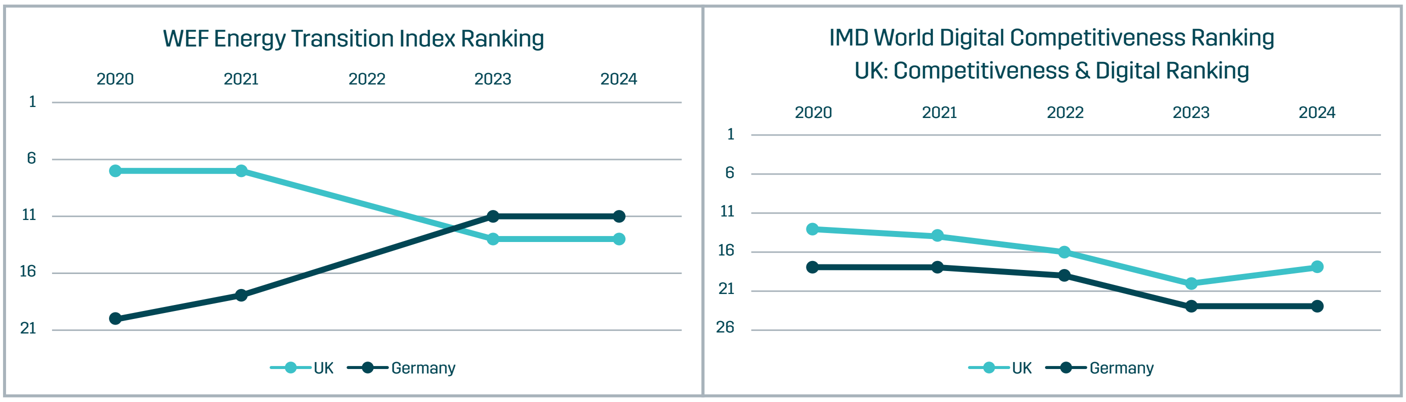
Norway's success underscores the importance of coordinated governance, robust infrastructure, and real-time data application, offering valuable lessons for other nations looking to bridge their digital adoption gaps. More detailed analysis is provided in Section 1.

Norway has achieved full-scale digital integration in its offshore oil and gas sector by fostering high trust between regulators and operators, establishing shared data platforms, and implementing long-term infrastructure investments. This combination has made Norway a leading example of system-wide digital transformation, where technology is seamlessly embedded across operations to enhance efficiency and sustainability.

[41] IMD (2024), 'World Digital Competitiveness Ranking 2024'
[42] World Economic Forum (2024), 'Energy Transition Index 2024'

24. Germany

Germany has established itself as a global leader in digital industrial transformation through its Industry 4.0 strategy, which integrates technologies like AI, IoT, and advanced automation into manufacturing. In energy, this foundation supports growing innovation in hydrogen, distributed grids, and the electrification of industry.



(Note: ETI not published for 2022.)

Figure 12 - Comparison between WEF and IMD Ranking (UK vs Germany)

Within the detailed metrics, Germany ranks high in the IMD for R&D intensity, technical education, and ICT development, but overall is lower than the UK. It performs well in sub-indicators such as legal environment and educational support. However, its energy-specific digital adoption has been more variable, with slower rollout in smart grid infrastructure and integration of renewables compared to some peers. Germany's strength lies in translating industrial innovation into scalable, exportable solutions.

By focusing on interoperability, technical standards, and widespread adoption across sectors, Germany has fostered a cohesive ecosystem that includes SMEs, robust digital infrastructure, and workforce training aligned with the needs of a digital economy. Cross-sector collaboration and secure data exchange, as well as public-private partnerships, accelerate the transition from research to industrial deployment.

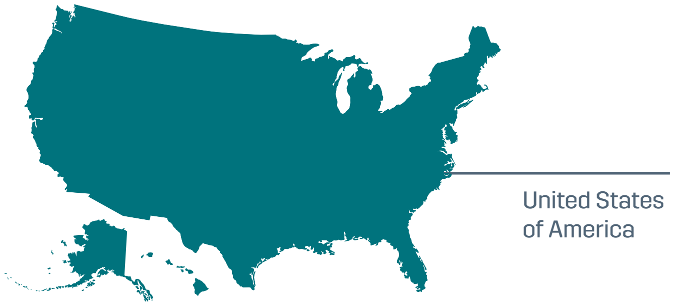
Since 2023, Germany has swapped places with the UK in its energy transition indices. This may be due to its long-term policy planning, efficient integration of innovation into operations, and strong emphasis on sustainability. Germany's experience highlights the importance of structured collaboration, SME support, and workforce reskilling, providing a model for the UK to address its adoption challenges, scale innovation, and embed digital technologies into the core of industrial operations.

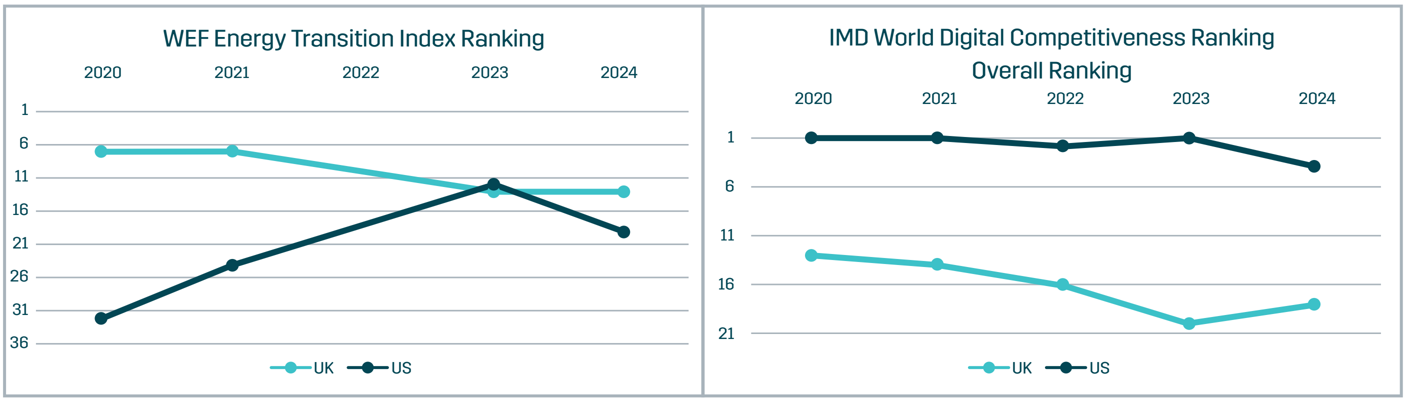
The UK leads Germany in overall digital competitiveness. However, Germany excels in educational sub-metrics, contributing to a more receptive workforce and higher digital adoption and literacy rates in organisations.

Germany has applied Industry 4.0 principles across various sectors, leveraging its robust manufacturing base and its tradition of government-industry collaboration. The country's focus on cyber-physical systems and platform technologies has been instrumental in driving energy innovation. However, the adoption of digital technologies in traditional energy systems remains uneven, presenting an opportunity for further development.

25. USA

The United States combines global leadership in digital competitiveness (4th in the IMD 2024 index) with deep energy system complexity and innovation capacity. Its energy sector includes both advanced renewables and legacy fossil infrastructure, making it a natural proving ground for automation, AI, and robotics.





(Note: ETI was not published for 2022.)

Figure 13 - Comparison between WEF and IMD Ranking (UK vs US)

Organisations routinely deploy digital twins, remote sensing, predictive maintenance, and autonomous systems across wind farms, pipelines, and offshore rigs. Federal agencies such as DOE and national laboratories support cross-sector testbeds, while major private-sector players lead in developing and scaling operational technologies. Although regulatory differences can lead to uneven adoption across states, the scale and pace of digital innovation in the US remains unmatched. The US model demonstrates how investment, experimentation, and strong public-private R&D pipelines can deliver digital integration in complex and decentralised energy systems.

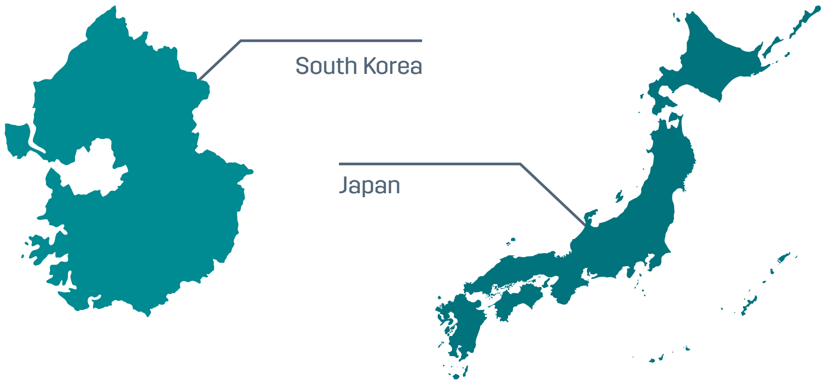
Despite its progress, the US faces challenges like modernising legacy infrastructure and addressing cybersecurity risks. However, its focus on workforce development, interoperability, and regulatory flexibility has provided a strong foundation for continuous advancement. In comparison, the United Kingdom excels in clean energy transformation but lags in digital competitiveness due to fragmented strategies and insufficient workforce skills. Lessons from the US, such as coordinated investment, ecosystem collaboration, and full-scale operational deployment, offer a roadmap for the UK to strengthen its digital adoption and industrial resilience.

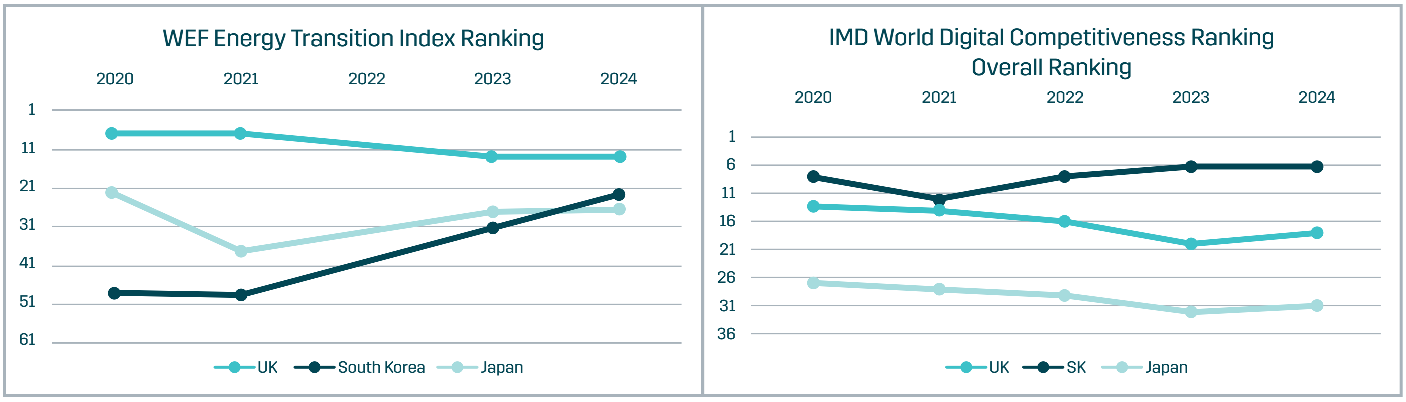
Overall, the US has set benchmarks in digital integration across its energy systems, positioning itself as a global innovator. By fostering collaboration between government, academia, and industry, and by prioritising real-world deployment over pilot projects, it exemplifies how nations can bridge the gap between research and practical implementation to achieve transformative results.

The United States stands as a pioneer in advanced robotics and automation within both traditional and renewable energy sectors. Its mature private sector, substantial R&D funding, and large-scale testbeds for technologies such as AI, digital twins, and predictive maintenance systems have positioned the country as a global leader in energy digitalisation. These advancements not only improve operational reliability but also accelerate the transition towards cleaner energy sources.

26. South Korea and Japan

South Korea and Japan have emerged as leaders in nuclear energy innovation and robotics, using complementary strategies to address energy security and foster technological advancement.





(Note: ETI was not published for 2022.)

Figure 14 - Comparison between WEF and IMD Ranking (UK vs South Korea and Japan)

South Korea excels in the development and export of nuclear systems coupled with embedded digital and robotic capabilities for operations and decommissioning. Japan focuses on advanced R&D in nuclear safety and robotics, investing in technologies like radiation-hardened drones and articulated arms for post-disaster environments, which have become benchmarks in nuclear decommissioning efforts. Both nations consistently integrate AI, digital twins, and automation into their nuclear frameworks, enhancing operational efficiency and safety.

Despite their strengths in nuclear energy and digital innovation, South Korea and Japan differ in global competitiveness rankings. South Korea ranks 6th in the IMD Digital Competitiveness Index, underpinned by workforce development and institutional collaboration, while Japan sits at 31st, excelling in robotics and scientific R&D but facing systemic challenges in digital transformation. In energy transition rankings, the UK outpaces both nations, holding 13th place due to its leadership in renewable energy deployment and policy commitment. South Korea's climb to 23rd and Japan's placement at 26th reflect their progress in nuclear systems and grid upgrades, though fossil fuel reliance remains a challenge for Japan.

The UK can draw lessons from South Korea's seamless integration of digital systems into nuclear operations and Japan's robotics expertise. By addressing its digital capability gaps, such as fragmented strategies, underdeveloped infrastructure, and workforce skill shortages, the UK could better leverage its energy transition leadership. South Korea and Japan demonstrate the importance of unified strategies, robust training programmes, and institutional alignment, offering valuable models for enhancing digital adoption across the energy sector.

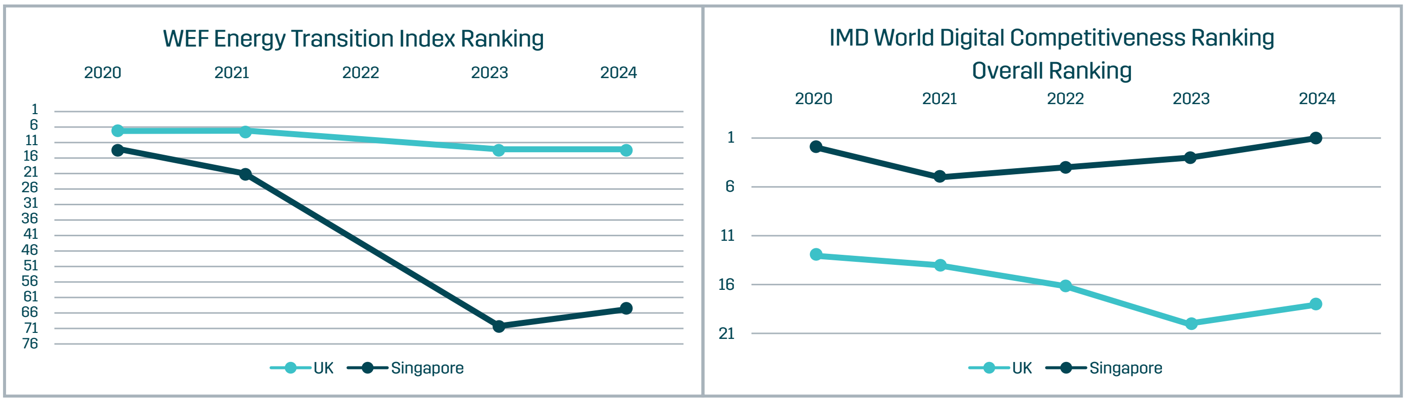
Both highlight the importance of investing not just in innovation, but in the systems and governance needed to deliver it at scale.

South Korea has made remarkable progress in nuclear digitalisation, supported by strong coordination between key agencies like KAERI and MOTIE. Ranked 6th in digital competitiveness and climbing from 48th in the Energy Transition Index (ETI) in 2020 to 23rd in 2024, South Korea's achievements are underpinned by a skilled workforce and significant investments in infrastructure.

Japan is renowned for its specialised robotics technology, particularly in nuclear decommissioning and safety-critical environments. Despite being ranked 31st in digital competitiveness, the nation maintains a strong global lead in R&D and scientific infrastructure. Its steady improvement in ETI performance, reaching 26th place in 2024, reflects ongoing efforts to apply advanced technologies to energy systems.

27. Singapore

Singapore exemplifies how a small, centralised country and city-state can deliver rapid, large-scale digital adoption in energy infrastructure. It ranks highly in the IMD index across categories such as regulatory agility, IT integration, and tech-driven education.



(Note: ETI was not published for 2022.)

Figure 15 - Comparison between WEF and IMD Ranking (UK vs Singapore)

Singapore's success is driven by long-term investment in digital infrastructure, public-private collaboration, and a clear governance model that links innovation goals with infrastructure delivery. While it is not a large energy producer, its district cooling, battery storage, and integrated EV infrastructure serve as testbeds for scalable technologies. Singapore's model is particularly relevant to the UK in terms of governance, speed of implementation, and cross-sector coordination.

Singapore has embraced digital energy transformation through coordinated initiatives that integrate advanced technologies into its energy infrastructure. Unlike the UK, which struggles with fragmented implementation and declining digital competitiveness, Singapore leverages strong public-private collaboration, long-term R&D investments, and cohesive government strategies to achieve operational excellence in energy digitalisation. With its unified policies and focus on workforce development, Singapore demonstrates how embedding innovation into live systems can accelerate the shift from testing to transformation.

While the UK outperforms Singapore in energy transition due to its leadership in renewables and regulatory frameworks, Singapore offers valuable lessons in digital adoption. Its approach highlights the importance of aligning national planning, institutional delivery, and cybersecurity with foundational trust and skills investment, providing a model for the UK. Singapore utilises its small geographical scale and centralised governance to rapidly implement digital solutions.

28. Summary

Each country was selected based on its advanced digital maturity, significant role in energy production, and distinct model of operational integration, automation, or innovation delivery. While each operates within different regulatory and industrial contexts, several consistent themes emerged.

Two thirds of the top 20 countries in IMD Digital Competitiveness are also in the top 20 of the Energy Transition Index, demonstrating the correlation between the two indicators.

In the figure below, this correlation is clearly apparent, and from the 2023 and 2024 data some observations and trends can be further highlighted.

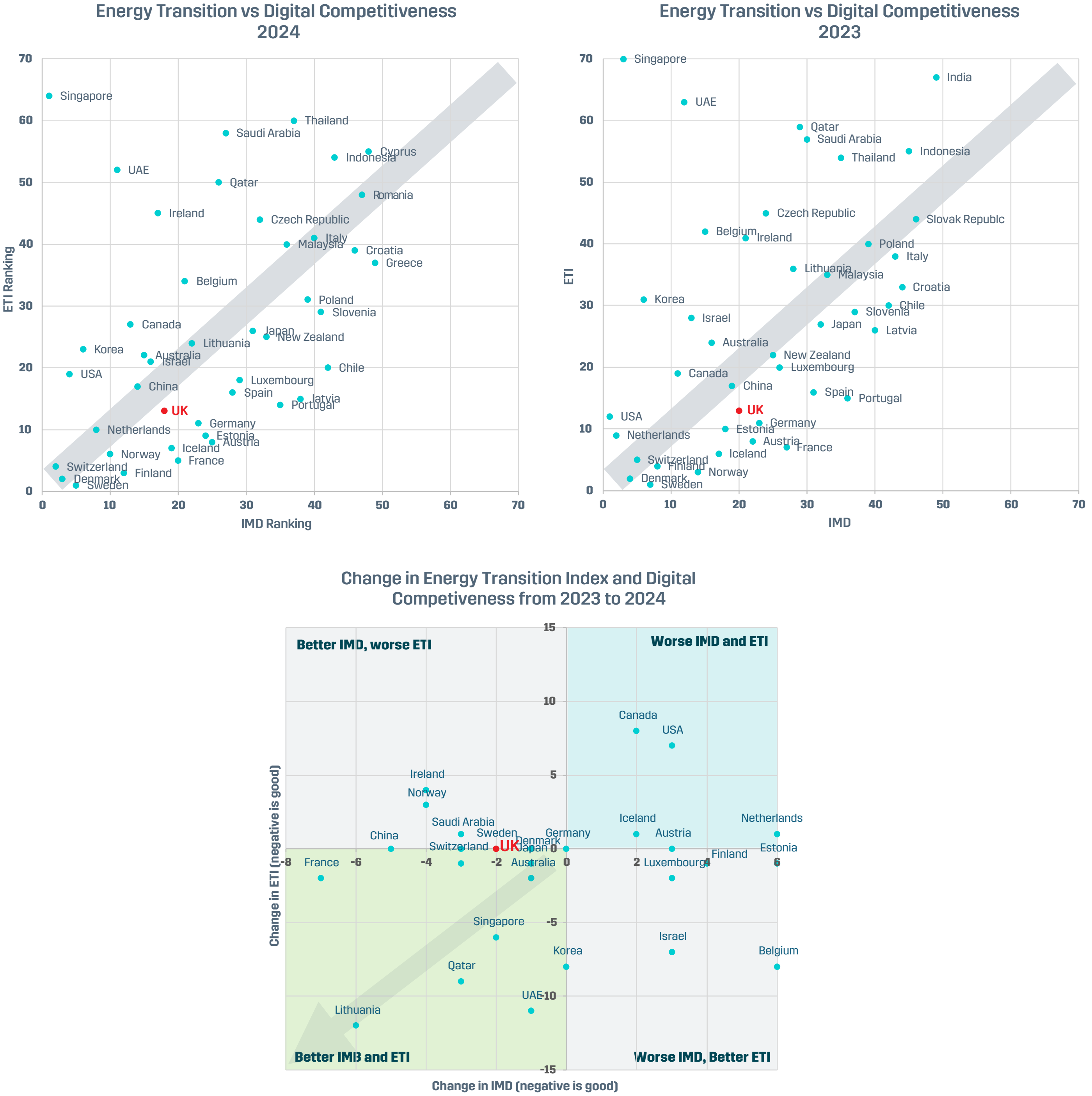


Figure 16 - Correlation between IMD and ETI and changes from 2023 to 2024

The Energy Transition Index (ETI) signifies those countries that are making significant progress on their current energy performance whilst also assessing readiness for transition. The Digital Competitiveness ranking (IMD) highlights those countries that are digitally mature in their adoption of technology, across all sectors. The lower left hand corner of the top two charts shows the most progressive countries, notably Scandinavia, Switzerland, Netherlands and the UK. Notably China has improved their digital competitiveness whilst ETI ranking has remained unchanged between 2023-24. USA and Canada have decreased in both ETI and IMD. The change in these rankings between 2023-2024 is shown in the lower figure where countries shown in the lower left hand quadrant have advanced in both ETI and IMD rankings. On this graph, the middle east (UAE, Qatar) has advanced more significantly than others, as has Singapore, as discussed earlier.

Successful digital adoption across all the countries analysed is underpinned by four key enablers:

- **Long-term investment:** Commitment to digital infrastructure and platforms like smart grids, robotics, and cloud systems lay the groundwork for innovation
- **Government-industry coordination:** Strong collaboration between government, industry, and research institutions to align goals and facilitate rapid delivery.
- **Workforce capability:** Development through technical education, public-private upskilling initiatives, and dedicated funding for research and development (R&D).
- **Operational integration:** Embedding technologies like AI, digital twins, and robotics into daily practices rather than limiting them to pilot projects or innovation labs.

While the UK ranks ahead of most peers in energy transition performance (13th in ETI 2024), it lags in digital readiness, ranked 18th, with low sub-scores in workforce training and business agility primarily. The global examples reviewed demonstrate that digital transformation is not driven by technology alone, but by coherent governance, targeted investment, and workforce strategy. These are areas where the UK can improve to match the pace of international leaders.

Digital Competitiveness ranking (IMD) highlights those countries that are digitally mature in their adoption of technology, across all sectors.

Gap Analysis
(UK strengths and weaknesses)

The UK is in a strong position to lead in the digital energy transition, but is held back by structural and operational barriers. The WEF Energy Transition Index and IMD WDC Ranking consistently show that while the UK has built the foundations for success, it is not yet achieving system wide transformation[43, 44]. Similarly, the Digital Future Index confirms the presence of innovation, but not adoption[45].

Without a coordinated effort to convert capability into outcomes, the UK risks remaining a nation of pilots rather than platforms. It is essential to bridge this gap and transition from potential to performance, especially in the energy sector, where there is a significant need for resilient, data-driven systems.

[43] World Economic Forum (2023), 'Fostering Effective Energy Transition'
[44] World Economic Forum (2024), 'Fostering Effective Energy Transition'
[45] Digital Catapult (2021), 'Digital Future Index 2021-2022'

29. Benchmark Overview

The United Kingdom has consistently positioned itself as a leader in digital innovation and clean energy policy. This section explores the UK's level of digital adoption, using global and sector-specific benchmarking data to assess how well the country is translating its innovation potential into real world impact, particularly in the energy sector.

A deeper analysis of key benchmarking frameworks reveals a growing disparity between a strong innovation capacity and the ability to translate that into widescale digital adoption and impact, particularly in sectors like energy. This section combines insights from the World Economic Forum's (WEF) Energy Transition Index, the IMD World Digital Competitiveness (WDC) Ranking, and Digital Catapult's Digital Future Index to explore the UK's digital maturity. By combining these methodologies, we gain a more complete view of where the UK excels, where it lags, and what this means for the future of the UK energy sector.

The figure above shows that while the UK initially held strong positions in both energy transition and digital competitiveness, it has seen a gradual decline in the latter[46], and a stagnation in energy transition performance since 2023[47,48,49,50].

This plateau in the WEF Energy Transition Index and the slip in the IMD WDC Ranking suggests that, although policy ambition and innovation potential remain intact, real-world delivery is stagnating. The UK is at risk of becoming digitally capable but operationally inefficient, particularly in translating innovation into impact across strategic sectors like energy.

It is important to note that these reports (WEF ETI and IMD WDC) are not sector specific. The Offshore Energy Data & Digital Maturity Survey 2023 is however, focused predominantly on the UK's oil and gas industry with some inclusion of renewable energy organisations[51]. The IMD WDC Ranking assesses national digital maturity across all sectors, while the WEF's Energy Transition Index specifically evaluates progress within energy systems globally.

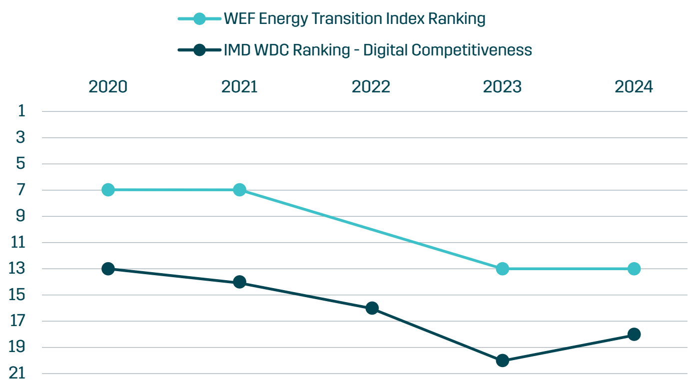


Figure 17 - Energy Transition Index (ETI) and World Digital Competitiveness (WDC)

The WEF Energy Transition Index measures real-world energy outcomes and system resilience whereas the IMD WDC Ranking examines the infrastructure and institutional readiness for digital transformation. Although for 2021-22, the Digital Future Index evaluates the UK's innovation potential, particularly in startups and research and development, without assessing actual adoption or sectoral integration. Note that at the time of the report, in 2021, the UK was ranked 7th (WEF ETI) and 14th (IMD WDC). It is fair to assume that the UK will have dropped from 3rd globally for 2024 on this basis.

The Digital Future Index report is best understood as a marker of potential. It confirms that the UK has the raw ingredients for leadership in digital technologies, but unlike the IMD WDC Ranking and WEF Energy Transition Index, it does not measure whether these capabilities are being scaled or embedded across the economy.

Index	UK Rank	Report Focus
WEF Energy Transition Index 2024	13 / 120	Energy transition performance, affordability, sustainability, & readiness
IMD World Digital Competitiveness Ranking 2024	18 / 67	Digital competitiveness, institutional agility, skills, and tech integration
DC Digital Future Index 2021-22[52]	3rd globally	Innovation capacity in AI, IoT, immersive tech, and startup ecosystems

Table 2 - Comparison of UK Ranking across different reports

[46] IMD (2024), 'IMD World Digital Competitiveness Ranking 2024'
[47] World Economic Forum (2020), 'Fostering Effective Energy Transition'
[48] World Economic Forum (2021), 'Fostering Effective Energy Transition'
[49] World Economic Forum (2023), 'Fostering Effective Energy Transition'
[50] World Economic Forum (2024), 'Fostering Effective Energy Transition'
[51] OEUK (2023), 'Offshore Energy Data & Digital Maturity Survey'
[52] Digital Catapult (2021), 'Digital Future Index 2021-2022'

30. Capability vs. Adoption

The UK exhibits a distinctive pattern of front-loaded digital maturity, characterised by robust research capabilities, a thriving startup environment, and ambitious policy initiatives. It also faces challenges in scaling ventures, workforce readiness, and widespread sector transformation.

IMD WDC Ranking sub-indices highlight challenges like those found in the Offshore Energy Data & Digital Maturity Survey 2023. The adaptability of companies places the UK at 54th[59], reflecting the surveys finding that many organisations struggle to adapt to digital change. In terms of Employee Training, the UK ranks 44th[60], supporting the surveys observation that digital skills are lacking, with only a third of energy firms feeling equipped[61]. Lastly, IT Integration sees the UK ranking 39th[62], with the survey noting ongoing issues with fragmented digital infrastructure and insufficient data strategies in UK energy organisations[63].

National weaknesses in digital competitiveness are clearly visible in the energy industry. Sector-specific digital maturity is both a reflection of and contributor to broader national trends.

Gap Area	Insight	Sectoral Implication
Skills & Training[53]	UK ranks 44th in employee training	Energy sector lacks talent to deploy and manage digital tools (e.g. AI, IoT, digital twins)
Infrastructure Investment[54]	53rd in telecom investment	Delays in broadband, IoT, and data-sharing infrastructure hinder smart energy systems
Scaling Innovation[55]	Few UK tech firms surpass £10M in revenue	Commercialisation of energy-focused startups remains slow
Energy System Performance[56,57]	ETI scores plateau since 2022	Affordability, equity, and flexibility not improving despite policy support
Industrial Uptake[58]	DFI finds low adoption in traditional sectors	Digital tools remain underused in manufacturing, construction, and energy

Table 3 - Key adoption gaps highlighted across the benchmarks

[53] World Economic Forum (2024), 'Fostering Effective Energy Transition'
[54] World Economic Forum (2024), 'Fostering Effective Energy Transition'
[55] Digital Catapult (2021), 'Digital Future Index 2021-2022'
[56] World Economic Forum (2023), 'Fostering Effective Energy Transition'
[57] World Economic Forum (2024), 'Fostering Effective Energy Transition'
[58] Digital Catapult (2021), 'Digital Future Index 2021-2022'
[59] World Economic Forum (2024), 'Fostering Effective Energy Transition'
[60] World Economic Forum (2024), 'Fostering Effective Energy Transition'
[61] OEUK (2023), 'Offshore Energy Data & Digital Maturity Survey'
[62] World Economic Forum (2024), 'Fostering Effective Energy Transition'
[63] OEUK (2023), 'Offshore Energy Data & Digital Maturity Survey'

31. Reasons for lag in digital adoption

Despite the UK's strong foundations in innovation and policy development, several persistent structural barriers continue to hinder digital adoption across the energy sector. Drawing from both national and sector-specific sources, four key themes emerge[64,65].

Fragmented Delivery

Despite multiple digital and energy strategies, implementation across government, regulators, and industry is disjointed with a lack of clear alignment or direction in digital efforts.

Workforce Skills Gap

The UK's education system generates considerable research output but falls short in applied digital skills, ranking 44th in employee training. The Offshore Energy Survey indicated that less than one-third of surveyed energy organisations are confident in their current digital skillset. The lack of scalable upskilling or reskilling programs aimed at mid-career professionals exacerbates this issue.

Infrastructure Limitations

Modern digital adoption requires robust infrastructure, yet the UK ranks 53rd for telecom investment, and Offshore Energy Survey finds that over 50% of surveyed organisations cite infrastructure and integration challenges as a core barrier to adoption. This infrastructure gap restricts the rollout of advanced energy technologies such as smart metering, flexible grid management, and decentralised energy platforms.

Data Strategy Gaps

Only 29% of UK energy organisations have a formal data strategy team. This lack of planning limits the deployment of digital tools such as predictive analytics and demand-side optimisation.

32. Bridging the Gap

To close the capability-adoption divide, the UK must act across four fronts.

Investment in digital skills

Involves developing programmes in data science, systems engineering, and AI, specifically tailored for energy. Focus on reskilling mid-career professionals in infrastructure-heavy fields.

Infrastructure acceleration is crucial

The UK should prioritise funding for smart grids, 5G deployment, and interoperable platforms. Organisations should be incentivised to participate in shared infrastructure planning to ensure a cohesive development strategy.

Support for scale-ups is essential

Investment should target companies that provide digital solutions for industrial and infrastructure sectors, including funding pathways beyond the startup phase, aiding their commercialisation and growth[66].

Integrated governance is necessary

Creating a national digital adoption strategy that links innovation clusters with infrastructure programmes and procurement reform is vital. This requires stronger alignment between public sector priorities and the needs of industry to ensure coherent and effective implementation[67].

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64 OEUK (2023), 'Offshore Energy Data & Digital Maturity Survey'
65 IMD (2024), 'IMD World Digital Competitiveness Ranking 2024'
66 Digital Catapult (2021), 'Digital Future Index 2021-2022'
67 IMD (2024), 'IMD World Digital Competitiveness Ranking 2024'

UK Barriers to Adoption

Digital technologies can transform the energy industry, but companies face adoption barriers. DNV surveyed 1,289 global industry professionals[68] to examine how digitisation can enhance performance. The figure below highlights key findings, consistent with broader literature. Some will be discussed below.

		All respondents (n=1289)	Digital Leaders (n=357)	Digital Laggards (n=482)
1	Resistance to change	36%	33%	39%
2	Cybersecurity risk	29%	36%	21%
3	Data quality/management issues	26%	27%	24%
4	Cost of digital transformations/technologies	26%	24%	28%
5	Lack of digital skills	26%	22%	32%
6	Lack of an effective digitalisation strategy	24%	14%	34%
7	Lack of investment	23%	19%	27%
8	Lack of data sharing within the energy industry	21%	25%	18%
9	Lack of industry standards	21%	25%	17%
10	Compatibility issues with partners and customers	20%	28%	14%

%s show the proportion of selecting each item among their organization's top three biggest barriers for the year ahead

Figure 18 - Top 10 Barriers to digitalisation (source DNV Energy Insights 2024)

[68] DNV (2024) 'Energy Industry Insights 2024: Leading a Data-Driven Transition'

Resistance to change

A major hurdle for both laggards and leaders. Energy companies manage hazardous systems, balancing innovation with risk minimisation. Job security and the perceived digital threat to jobs leads to resistance to digitalisation and new ways of working. Organisations are not incentivised to use pioneering methods to solve problems, and the risk-averse nature of energy compounds the hesitancy to invest.

Cybersecurity risks

Many assets have immature connectivity and data architecture, insufficient for many digital solutions. Moving to cloud-based systems and deployment of connected devices substantially increases exposure cybersecurity risks. Protecting critical energy infrastructure from cyberattacks represents a significant challenge that requires ongoing investment and expertise.

Data quality/management and maturity

Data silos are prominent within the industry, reducing data accessibility for analytics. A critical challenge identified in multiple studies is the lag in data maturity within the energy sector. Many organisations have not developed comprehensive data strategies or governance frameworks, limiting their ability to leverage digital technologies effectively.

Cost/benefit

Digital innovators and companies face high investment costs, regulatory hurdles, and limited access to infrastructure and technology. Without clear guidelines or financial support, they hesitate to enter energy markets. Few assets are designed for digital technology, making retrofitting expensive. Unclear problem statements and lack of use cases lead to weak business cases for investment.

Lack of digital skills

There is a lack of digital skilled workers working towards decarbonisation of the energy[69]. Approximately 40% of businesses within the energy sector report difficulties hiring skilled professionals in data science, cybersecurity, artificial intelligence, and system integration. This can significantly impede progress in digital adoption as organisations struggle to implement and maintain sophisticated digital systems.

Lack of a digital strategy

It is difficult to maintain safe and secure innovation alongside rapid innovation cycles[70]. There is also disparity between operators for their R&D capabilities due to their varying size and portfolio of assets. This often leads to procuring off-the-shelf solutions that may be inflexible to operator's needs and is costly. Without a strategy and clear business priorities, digital technologies can fail to deliver.

Lack of data sharing

Historically, data use in the UK energy sector has been constrained by fragmentation, with information collected and held by multiple stakeholders with limited sharing between them[71]. This fragmentation creates inefficiencies and prevents the development of system-wide digital solutions.

Lack of standards

Many energy assets are old and are not designed for digital. They do not have the required connectivity and data architecture for digital solutions[72]. The lack of regulations and incentives discourages operators to invest.

Compatibility with partners and customers

As asset ownership is transferred, systems quickly become difficult to integrate. Different safe systems of work, permit to works, and isolation certificates across assets further complicate technology deployment. Lack of access to advanced testing facilities, limited exposure to digital solutions, and relatively low levels of collaboration inhibit adoption.

Lack of collaboration

Competition amongst operators creates a barrier for collaboration, even in joint ventures where partners may work on digital solutions in silos. Energy operators struggle to commercialise and adopt innovative digital technologies due to a lack of access to advanced testing facilities, limited confidence in digital solutions, and low levels of help finding appropriate collaboration partners.

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[69] Digital Catapult (2024), 'Digital Solutions for the Energy Sector'
[70] DNV (2024), 'Energy Industry Insights 2024: Leading a Data-Driven Transition'
[71] UK Parliament Post Note 655 (2021), 'Energy Sector Digitalisation'
[72] NZTC (2024), 'Advancing Remote Operations'

Conclusion

The United Kingdom's energy sector is currently experiencing a significant phase of digital transformation, with varying levels of technology adoption across different segments such as oil and gas, renewables, hydrogen, and carbon capture, utilisation, and storage (CCUS). The fossil fuels sector is at the forefront of integrating technologies like artificial intelligence (AI) for predictive maintenance, simulation, and modelling. Meanwhile, renewable energy sectors are increasingly utilising AI for forecasting, asset optimisation, and grid management. Emerging sectors like hydrogen and CCUS indicate promising but less mature levels of adoption, primarily driven by research initiatives and pilot projects.

Despite these advancements, the industry demonstrates broad but shallow digital adoption, lagging behind international benchmarks set by countries such as Norway regarding the depth of implementation. Achieving the UK's 2050 net-zero targets will necessitate a cohesive and multi-dimensional approach that leverages advanced technologies such as digital twins, robotics, and smart grids to enhance efficiency, reduce costs, and effectively integrate renewable energy while addressing structural barriers and fostering sector-wide connectivity.

The UK's industrial energy sector faces several challenges in achieving comprehensive digital transformation, including issues related to data interoperability, skills development, and regulatory clarity. Addressing these obstacles could expedite the energy transition necessary to meet net-zero objectives. Progress remains hindered by fragmented approaches and insufficient collaboration between stakeholders, coupled with a lack of scalable mechanisms to promote digital adoption. This report underscores the importance of a multi-faceted strategy and industrial-scale assurance to deploy digital solutions effectively.

One of the most significant challenges is overcoming resistance to change, often driven by job security concerns, risk aversion, and high investment costs. Additionally, discrepancies in data-sharing standards, outdated infrastructure, and an uneven distribution of digital skills across the workforce compound these issues. The UK has the opportunity to learn from the successes of other nations while leveraging its rich history of innovation to address these gaps comprehensively and collaboratively.

Norway exemplifies successful digital transformation within the energy sector, demonstrating high levels of digital adoption that bolster both digital competitiveness and energy transition performance. Key factors contributing to this success include coordinated governance, sustained investments, and workforce development. Examples from global leaders such as Norway, Germany, and South Korea highlight the importance of shared data platforms, Industry 4.0 principles, and workforce training as essential strategies for achieving digital maturity and scaling innovative projects efficiently.

To bridge the gap and navigate the complexities of digital transformation, the UK must prioritise several strategic recommendations.

- Firstly, fostering greater collaboration across the energy sector, including cross-sectoral partnerships with other industries, is crucial to establish a unified and effective energy transition. Scaling up mechanisms such as digital hubs and shared data standards will enhance knowledge sharing and operational efficiency, focusing on testing and proving innovative technologies in real-world contexts to ensure their relevance and feasibility.
- Secondly, policies that provide regulatory clarity and stability, particularly around emerging technologies like hydrogen and CCUS, will lay the foundation for sustainable investment and innovation. These regulations should incorporate frameworks for assurance and benchmarking, enabling the sector to adopt digital solutions with greater confidence.
- Thirdly, investing in workforce development and digital skills must remain a cornerstone of the strategy. Tailored training programs, strong partnerships with educational institutions, and industry-specific apprenticeships will prepare the workforce to manage the challenges and opportunities presented by digitalisation. Additionally, efforts must focus on addressing cybersecurity concerns, critical for building trust and protecting the integrity of digital systems.

For the UK energy sector to advance its energy transition and enhance global competitiveness, it must fully embrace digital transformation through a deeper adoption of advanced technologies. While progress is evident, it remains uncoordinated and slow, limiting potential benefits. A strategic focus on improving communication infrastructure and evolving commercial models is essential to incentivise adoption, reduce barriers, and foster innovation.

In conclusion, the UK is at a critical juncture where faster and more effective adoption of digital technology in the energy sector is essential. Despite persistent challenges, there is a significant and urgent opportunity to build on the achievements of global leaders and a strong legacy of innovation. Establishing confidence, shared best practices, and ensuring technology is industry-ready are critical. With enhanced connectivity across the ecosystem, digitalisation must become the cornerstone of the UK's sustainable energy future. By adopting a forward-thinking, collaborative, and strategic approach, the UK can transform its energy sector into a global leader, supporting economic growth, environmental sustainability, and societal wellbeing for decades to come.

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Appendix A - Scoring and Analysis

Each energy sector from Section 12 will be scored based on the adoption levels of the digital technologies listed in Section 14.

Adoption will be considered in the context of the energy carrier, or electricity generated, as listed below. For CCUS, Carbon Capture will be covered within the Production column below.

The electricity network will be discussed in a separate section.

Energy Sector	Production		Storage		Transport		Utilisation	
	Fuel	Elec	Fuel	Elec	Fuel	Elec	Fuel	Elec
Fossil Fuels	✓	-	✓	covered within Electricity Network	✓	covered within Electricity Network	-	covered within Electricity Network
Hydrogen	✓	✓	✓		✓		-	
Nuclear	-	✓	✓		-		-	
Solar	-	✓	-		-		-	
Wind	-	✓	-		-		-	
Geothermal	-	✓	✓		✓		-	
Wave, Tidal and Hydro	-	✓	-		-		-	
CCUS	✓	-	✓		✓		-	
Electricity Network	-	-	-	✓	-	✓	-	✓

Table 4 - Areas for scoring consideration for each energy sector
The scoring framework is duplicated here for reference.

1. **No Adoption:** The technology is not used or has negligible presence.
2. **Initial Exploration:** Pilot projects or minimal use exist, but adoption is not widespread.
3. **Early Adoption:** Limited deployment in specific applications, with some operational impact.
4. **Moderate Adoption:** Technology is used in several areas, with noticeable benefits, but not fully integrated.
5. **Significant Adoption:** Widespread use with substantial operational impact, though not universal.
6. **High Adoption:** Near-complete integration across most relevant applications, with mature implementation.
7. **Complete Adoption:** Fully embedded across all applicable areas, representing industry-leading practice.

Figure 19 - Scoring framework

33. Fossil Fuels

Fossil fuels refer to natural energy resources such as coal, oil, and natural gas. In the industrial energy context, they serve as primary inputs for energy generation, powering manufacturing, transportation, and large-scale operations. Despite their high energy density and reliability, they are associated with significant environmental challenges, including greenhouse gas emissions and resource depletion.

Industrial sectors increasingly explore ways to optimise their use, incorporating many digital technologies to improve efficiency, reduce emissions, and transition to more sustainable practices while maintaining energy security and operational continuity.

Artificial Intelligence

AI and machine learning help optimise different operations, making them more cost-efficient and reducing carbon emissions during production, transmission, and distribution. They also support predictive maintenance of operational assets like oil platforms, pipelines, and refineries, preventing downtime and improving safety[73]. AI can process massive volumes of data from exploration, drilling, and production operations, helping companies make more informed decisions. The algorithms are capable of optimising drilling processes, predicting equipment failure, and even analysing geological data to identify new reserves.

It is highlighted that nearly half (47%) of the oil and gas industry professionals surveyed by DNV say that their organisations will use AI in operations in 2024. However, only 15% of respondents say their organisations are using AI in live, day-to-day operations, and only 3% report highly integrated and/or advanced use of AI. This indicates that, while there is significant interest and planning for AI adoption, actual implementation and integration remain limited.

Compared to other energy sectors, the oil and gas industry has been an early adopter of AI, to optimise exploration, production, maintenance and safety[74]. The UK oil and gas sector is increasingly embracing Artificial Intelligence (AI) and machine learning (ML) as vital tools for enhancing productivity, reducing costs, and improving safety. The integration of AI and ML facilitates more informed decision-making and boosts overall operational efficiency, and recent analysis[75] suggests that AI-powered maintenance solutions have the potential to reduce maintenance costs by up to 40%, presenting a significant economic driver for adoption within the sector.

Predictive AI algorithms are being deployed to analyse extensive datasets, enabling the anticipation of equipment malfunctions, the scheduling of targeted repairs, and the optimisation of budget allocation, thereby minimising costly downtime.

Shell has reported a significant reduction of 20% in unscheduled downtime and a 15% decrease in maintenance costs through the implementation of predictive maintenance AI across its operational rigs[76]. This demonstrates a tangible return on investment and highlights the practical benefits of AI in enhancing the reliability and efficiency of oil and gas production.

AI and ML are becoming indispensable tools for data analysis in oil and gas. By 2030, 60% of oil and gas executives anticipate digital technologies and AI will have a major impact on their businesses[77]. However, evidence such as this indicates that, whilst AI is progressing well within the fossil fuels (predominantly oil and gas) sector, widespread and complete adoption is still some way off.

The summary of scores for the three identified areas of fossil fuel production, storage and transport is shown below with justification provided in the following sub-sections.

Fossil Fuels	Production	Storage	Transport
	Fuel	Fuel	Fuel
Artificial Intelligence	5	5	4

Table 5 - Fossil fuels: Artificial Intelligence Score

[73] DNV (2024, March), 'AI spells opportunity and manageable risk for the oil and gas industry'
[74] IEA (2025), 'Energy and AI'
[75] Datategy (2024), 'How can AI revolutionize risk management in Oil & Gas'
[76] Sandtech (2025), 'Drilling Down: How AI is Changing the Future of Oil and Gas
[77] Bain & Company (2023), 'State of the Transition 2023: Global Energy and Natural Resource Executive Perspectives'

Fuel Production

While there is growing interest and pilot projects exploring the use of AI for predictive maintenance of heavy equipment and assets[78], widespread mature adoption is not yet evident across all operations. The sector is exploring AI's potential in optimising drilling operations and reservoir management[79]. As a result, for upstream production (drilling and exploration) of UK oil and gas operations, a score of 5 (significant adoption) indicates widespread use.

Fuel Storage

With use of AI for predictive maintenance of storage tanks, and for integrity monitoring[80], AI adoption in the storage of oil and gas is estimated to have a score of 5 (significant adoption).

Fuel Transport

There is potential being explored for AI in pipeline monitoring, anomaly detection, and logistics optimisation within the sector[81] and a score of 4 indicates AI application in some areas but not widely.

Remote Operations

The Advancing Remote Operations (ARO) project, delivered by NZTC, aimed to accelerate the adoption of digital technologies to reduce the carbon footprint associated with personnel living and working offshore. This included the use of sensors, data transmission, and data storage technologies to support real-time decision-making, enhance reliability, and deliver increased production rates alongside reduced maintenance spend and asset life extension[82]. With some industry claims of reducing human interventions via helicopter by 60%, a saving of £1.4m per platform, the potential benefits are significant[83].

The NZTC-led landscape study[84] highlighted that industry has struggled to adopt and scale integrated digital technologies for remote capabilities across legacy assets. However, there is an increasing need for operators to synchronise their operations and make data-driven decisions to enhance efficiency and reduce costs.

Similar to the levels of adoption of remote operations, the level of maturity of remote operations technology can also be assessed, where initial deployments focus on remote monitoring (of data and systems), moving to remote control (with limited direct control of component behaviour and control functions), to autonomous operations (fully automated operations and control). Within this section, the extent of the adoption is the focus rather than the levels of maturity and it should be noted that the dominant form of remote operations is that of remote monitoring rather than fully autonomous operations.

The summary of scores for the three identified areas of fossil fuel production, storage and transport is shown below with justification in the following sub-sections

Fossil Fuels	Production	Storage	Transport
	Fuel	Fuel	Fuel
Remote operations	5	4	4

Table 6 - Fossil fuels: Remote Operations Score

78 EY - US (2025), 'Maximising the impact of AI in the oil and gas sector'
79 IT Pro (2024), 'How the oil and gas industry is using AI to maximize production'
80 Offshore.Technology.com (2024), 'Oil and gas firms turning to digital twins for generating actionable insights'
81 Sandtech (2025), 'Drilling Down: How AI is Changing the Future of Oil and Gas - Sand Technologies'
82 NZTC (2024), 'Advanced Remote Operations (ARO) Playbook'
83 ITI Group, 'Remote Operations and Minimum Manning Solutions'
84 NZTC (2024), 'Advancing Remote Operations'

Fuel Production

Oil and gas companies are increasingly installing sensors on equipment that transmit data via IT networks, facilitating real-time monitoring and responsive control from remote locations. This allows for the anticipation of equipment malfunctions and the scheduling of targeted repairs, minimising the need for on-site intervention.

Fugro achieved a significant milestone by performing the first fully remote inspection of an oil and gas platform in UK waters, utilising a remotely operated vehicle (ROV) controlled from its state-of-the-art remote operations centre (ROC) in Aberdeen[85]. This demonstrated the proficiency and potential of remote operations in enhancing safety and efficiency. Oceaneering also operates an onshore remote operations centre (OROC) in Aberdeen[86], providing comprehensive support for offshore operations, including inspections and maintenance, thereby reducing the need for offshore personnel and minimising environmental impact.

Remote operations adoption in UK oil and gas production is at a level 4, indicating moderate levels of adoption. There is increasing interest in monitoring and control of offshore platforms, well testing, and unmanned facilities.[87]

Fuel Storage

Remote operations are being implemented in UK oil and gas fuel storage to enhance safety, efficiency, and reduce the need for on-site personnel. Digital tools and sensors enable the remote monitoring of storage tanks, allowing operators to have a real-time overview of the storage facility's status from a central control room, facilitating quicker responses to any anomalies or potential issues. Remote valve control and automated processes can also be implemented to manage the flow of fuel into and out of storage tanks, further improving operational efficiency and safety.

Remote operations adoption in oil and gas storage, e.g. monitoring of pressure vessels, scores highly (6) given the safety considerations and need for safety assurance.

Fuel Transport

Remote operations are increasingly important for the monitoring and maintenance of fuel transmission pipelines in the UK oil and gas sector, to enable the remote monitoring of pipeline integrity, leak detection, and operational parameters from centralised control rooms. The ability to conduct remote inspections and monitor pipeline conditions in real-time enhances the safety and efficiency of fuel transmission operations, allowing for quicker detection and response to potential issues.

Remote operations adoption in oil and gas transport also scores highly (6) given the safety critical components that exist, and the need for monitoring of components at all times.

Digital Twins

Digital twins are virtual representations of physical assets, systems, or processes that mirror their real-world counterparts. These twins are created through a combination of various means, from reality capture (laser scanning, photogrammetry) to digital models arising from modelling/authoring tools such as CAD.

Integration of other technologies such as sensor and IoT device data, simulation and modelling data, data analytics, information insights, data visualisation, all enable digital twins to provide insights that are beyond the raw data obtained from measurements alone.

In the energy sector, digital twins are used to model and simulate various operational and off-design conditions such as failure scenarios, extreme weather events, cyber-attacks, and equipment failures. These help operators proactively mitigate risks, minimise downtime, and ensure continuity of service[88]. Major players in the UK oil and gas sector, such as BP, are actively deploying digital twins. BP's APEX system, for example, maps oil and gas production in the North Sea to improve operational efficiency and reduce energy emissions, resulting in a notable increase of 30,000 barrels in BP's global production. Similarly, Shell utilises digital twin technology in partnership with companies like Kongsberg Digital to simulate various operational scenarios, optimise energy consumption, and enhance production efficiency across its asset portfolio.

The summary of scores for the three identified areas of fossil fuel production, storage and transport is shown below with justification in the following sub-sections.

[85] Fugro (2020), 'Fugro performs first fully remote platform inspection on UK Continental Shelf'
[86] Oceaneering, 'Onshore Remote Operations Centers (OROCs)'
[87] Kent (2022), 'The move from local control to remote operations of Oil & Gas facilities - Kent
[88] NZTC (2025), 'RDEN Digital Centre of Excellence - Outline Business Case' (document internal to NZTC)

Fossil Fuels	Production	Storage	Transport
	Fuel	Fuel	Fuel
Digital Twins	5	4	4

Table 7 - Fossil fuels: Digital Twins Score

Fuel Production

Digital twin technology is recognised as a crucial element in the digital transformation of the UK oil and gas industry, providing virtual replicas of physical assets such as machinery, wells, pipelines, and platforms. These virtual representations enable the simulation of real-time operating scenarios, allowing companies to leverage data analytics for the early prediction and resolution of potential issues. This proactive approach leads to a reduction in machine downtime and operational costs, alongside improvements in overall optimisation.

Digital twins also contribute to enhancing structural integrity and facilitating the advancement of new structural designs in alignment with efficiency and optimisation objectives.
Major players in the UK oil and gas sector, such as BP, are actively deploying digital twins. BP's APEX system, for example, maps oil and gas production in the North Sea to improve operational efficiency and reduce energy emissions, resulting in a notable increase of 30,000 barrels in BP's global production. Similarly, Shell utilises digital twin technology in partnership with companies like Kongsberg Digital to simulate various operational scenarios, optimise energy consumption, and enhance production efficiency across its asset portfolio[89].

Digital twin adoption in UK oil and gas production is scored at 5, showing significant adoption. There is growing interest and application of digital twins for asset monitoring, predictive maintenance, simulation of drilling scenarios, and optimisation of production workflows[90].

Fuel Storage

Digital twin technology is increasingly being adopted for fuel storage facilities in the UK oil and gas sector, providing virtual replicas of storage tanks, pipelines, and associated equipment. These digital twins enable real-time monitoring of the physical assets, allowing operators to analyse performance data, predict potential failures, and optimise storage operations[91]. By simulating various scenarios, digital twins can help in identifying potential hazards, planning maintenance activities more effectively, and ensuring compliance with safety regulations.

Companies are leveraging digital twins for predictive maintenance of storage assets, aiming to reduce unplanned downtime and extend the lifespan of critical infrastructure[92]. The ability to virtually inspect and analyse storage facilities through digital twins also improves workforce efficiency and reduces the need for costly and potentially hazardous on-site inspections[93].

Digital twin adoption in oil and gas storage is scored at level 4, with early exploration. Initial efforts are to explore digital twins for tank monitoring, ensuring integrity, and optimising storage operations.

Fuel Transport

Digital twin technology is being adopted in the UK oil and gas sector for the transmission of fuel, providing virtual representations of pipeline networks and associated infrastructure. These digital twins enable real-time monitoring of pipeline conditions, allowing operators to track parameters like pressure, flow rate, and temperature. By simulating various operational scenarios and potential failure modes, digital twins can help in predicting and preventing pipeline incidents, optimising transmission efficiency, and planning maintenance activities effectively. They also facilitate better collaboration among different teams involved in pipeline operations and maintenance by providing a shared virtual environment for analysis and decision-making.

Digital twin adoption in oil and gas transport is scored at 4, indicating moderate adoption. There is potential for increased use of digital twins for pipeline integrity management, flow optimisation, and simulating the flow physics within existing infrastructure.

[89] Digital Twin Insider (2024),'Leading Digital Twin Providers Transforming the Energy Sector: Innovations in Efficiency and Emissions Reduction'
[90] Offshore-Technology.com (2024), 'Oil and gas firms turning to digital twins for generating actionable insights'
[91] Cupix (2025), 'Digital Twins Transform Operational Efficiency in Oil and Gas
[92] Offshore Technology Focus (2024), 'Oil and gas firms turn to digital twins for generating actionable insights
[93] Acuvate (2025), 'How Digital Twins Are Transforming Oil and Gas Industry in 2025'

Robotics and Autonomous Systems

Robotics and autonomous systems are used in offshore energy installations to perform tasks that are hazardous or difficult for humans. These include aerial, on-asset and underwater inspections as well as monitoring of component behaviour, leaks/venting and delivery of small packages and small components such as spares.

Robots are expected to be more reliable than humans[94] especially in challenging situations, and are capable of working continuously, maintaining precision and efficiency[95].

Companies such as Equinor, TotalEnergies, and Shell are deploying them to work alongside humans on offshore sites[96]. Robotic automation can manage remote operations, such as those conducted on Equinor's Oseberg H platform in the North Sea. Their ability to perform repetitive and mundane tasks with minimal errors is saving time and internal resources for companies. Furthermore, it allows them to deploy field technicians on more critical issues.

The summary of scores for the three identified areas of fossil fuel production, storage and transport is shown below with justification in the following sub-sections.

Fossil Fuels	Production	Storage	Transport
	Fuel	Fuel	Fuel
Robotics and Autonomous Systems	4	4	4

Table 8 - Fossil fuels: Robotics and Autonomous Systems Score

Fuel Production

Robotics and autonomous systems are progressively being integrated into the UK oil and gas sector, particularly in offshore operations, to enhance safety and reduce costs associated with manual tasks. The automation of traditionally human-intensive operations, such as pipe handling, Blowout Preventer (BOP) handling, and fluid system management on rigs, presents significant opportunities for improving safety and operational efficiency. Drones are adept at performing aerial inspections of pipelines and facilities, eliminating the need for comprehensive manual inspections in hazardous or difficult-to-access areas. Petrobras, for instance, has partnered with robotics startup ANYbotics to automate asset inspection processes at its offshore sites, highlighting the growing trend of leveraging robotics for routine and potentially hazardous tasks within the industry.[14]

Robotics adoption in UK oil and gas production is at a level 4, with increasing implementation. Robots are being increasingly used for hazardous tasks, inspections, maintenance activities, and automating certain drilling operations[97].

Fuel Storage

Robotics and autonomous systems are finding applications in the maintenance and inspection of fuel storage tanks within the UK oil and gas sector. Internal robotic crawlers equipped with cameras and various sensors can be deployed to inspect the inside of storage tanks for corrosion, cracks, or other defects, providing detailed visual and non-destructive testing data without requiring human entry into confined spaces[98]. These robots can navigate complex tank geometries and provide comprehensive assessments of the tank's structural integrity.

Additionally, robots can be used for cleaning storage tanks, removing sediment and other build-up, which can improve efficiency and extend the lifespan of the tanks. The deployment of such robotic systems enhances safety by minimising human exposure to hazardous environments and improves the thoroughness and accuracy of inspections and maintenance activities.

Robotics adoption in oil and gas storage is at a level 4, suggesting moderate adoption. Automation of some tasks in refineries and processing plants, including tank cleaning, is being seen, however.

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[94] NZTC (2024), 'OLTER Skills and Talent Report'
[95] NZTC (2024), 'OLTER Offshore Energy RAS Report'
[96] GlobalData (2024),'Robotics in Oil and Gas - Strategic Intelligence'
[97] NRI Digital (2023, Issue 93), 'Case studies: robotics in the oil and gas industry - Offshore Technology Focus'
[98] Shell Global, 'Robotics in the Energy Industry'

Fuel Transport

Robotics and autonomous systems are being developed and deployed for the inspection, maintenance, and repair of fuel transmission pipelines in the UK oil and gas sector. Pipeline inspection robots, including remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs), are equipped with cameras and sensors to detect corrosion, cracks, and other defects along the pipeline[99]. These robots can navigate long distances and provide detailed condition assessments without disrupting the flow of fuel.

The use of robotics in pipeline maintenance reduces the need for human intervention in potentially hazardous environments and improves the accuracy and efficiency of inspection and repair tasks.

Robotics adoption in oil and gas transport is at level 4, showing moderate levels of adoption.

Cybersecurity

Cybersecurity has become a paramount concern for the UK oil and gas sector, driven by the increasing reliance on digital technologies and the interconnectedness of operational systems.

Petroleum companies face daily cyber threats ranging from hydrocarbon installation terrorism to industrial espionage, underscoring the critical need for robust security measures. The integration of web-based communication and storage technologies has expanded the attack surface, increasing the risk of hackers targeting sensitive data and critical infrastructure.

A successful cyberattack can lead to severe consequences, including plant closures, production disruptions, significant financial losses, and even physical damage to facilities.

Given the maturity and necessary levels of cybersecurity that need to be in place for fossil fuel assets to operate, the scoring is inherently high, scoring 6 for all areas.

The summary of scores for the three identified areas of fossil fuel production, storage and transport is shown below.

Fossil Fuels	Production	Storage	Transport
	Fuel	Fuel	Fuel
Cybersecurity	6	5	6

Table 9 - Fossil fuels: Cybersecurity Score

[99] Yu, Yang, Ren, Luo, Dobie, Gu, Yan (2019), 'Inspection Robots in Oil & Gas Industry: a Review of Current Solutions and Future Trends'

Summary and Overall Scoring

In summary, for the fossil fuels sector, there is a fairly mature adoption and use of digital technologies with more adoption within fuel production (drilling/production) as opposed to fuel storage or transportation. Fuel transportation (pipelines primarily) was understood to have a slightly lower level of adoption of AI and robotics applications. Equally, remote operations technology and digital twin applications were more prevalent for production due to the requirement for ongoing monitoring and operational insights.

The challenge facing this industry is that of keeping the technology current and up to date.

Fossil Fuels	Production	Storage	Transport
	Fuel	Fuel	Fuel
Artificial Intelligence	5	5	4
Remote Operations	5	4	4
Digital Twins	5	4	4
Robotics and Autonomous Systems	4	4	4
Cybersecurity	6	5	6

Table 10 - Fossil fuels: Overall scoring

In summary, while the Oil & Gas sector in the UK has made strides in adopting AI/ML technologies, there are still significant barriers that need to be addressed to fully realise the potential of these technologies. These include[100]

- challenges in developing business cases for modern technologies
- lack of access to advanced testing facilities
- limited exposure for digital solutions, and relatively low levels of collaboration.
- trust is also a significant barrier, as AI/ML technologies need to be validated and verified to ensure they meet stakeholder expectations and comply with regulations.
- cybersecurity risks, as connecting AI/ML to critical control systems and data sources creates potential opportunities for external attack.
- Regulatory changes can make it difficult for organisations to benefit from AI, as the design or use of AI could contravene laws on privacy, transparency, cybersecurity, and safety.

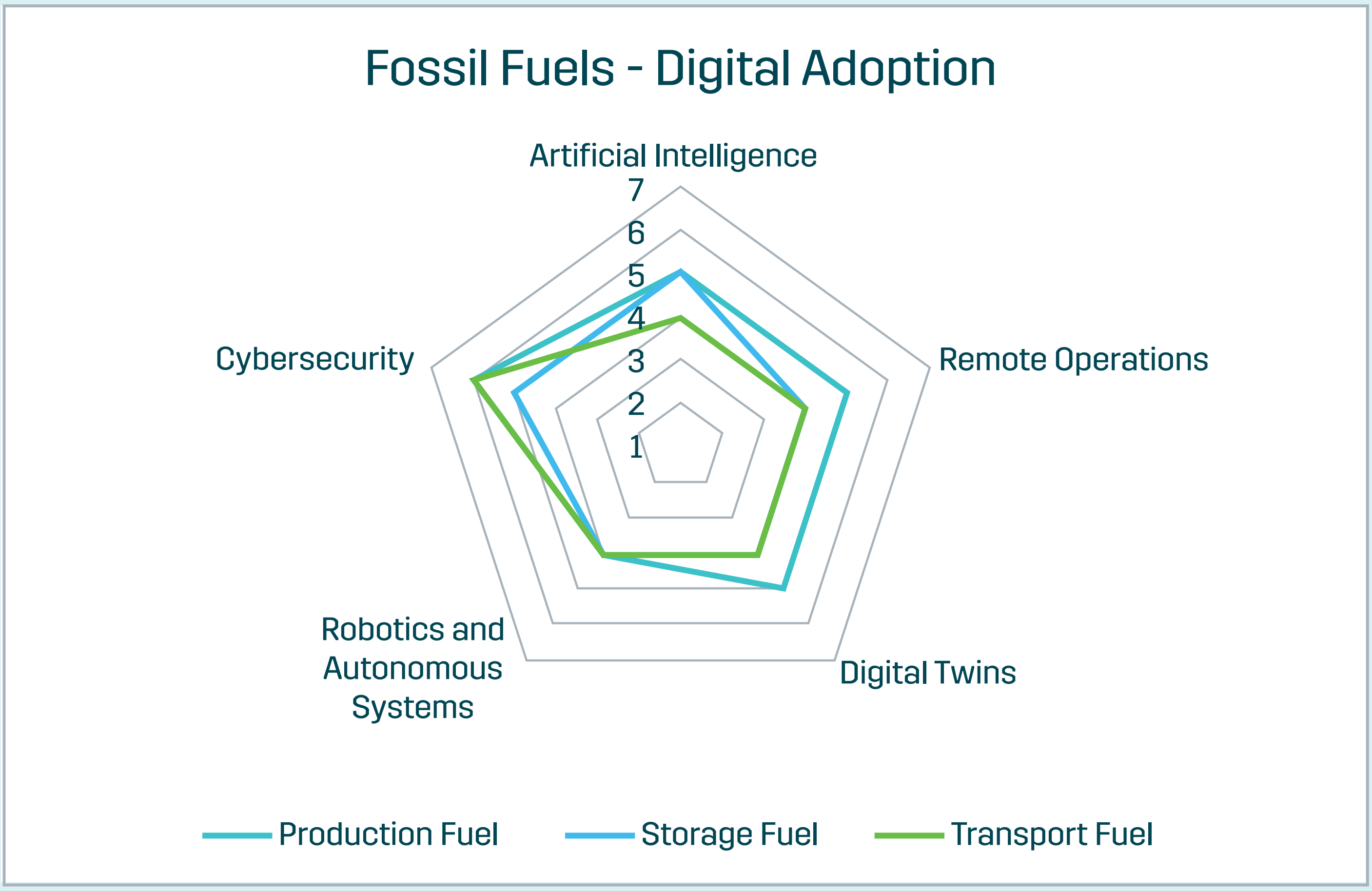

Figure 20 - Fossil Fuels Score

[100] ROCE Business Case

34. Hydrogen

Integrating hydrogen into energy systems at scale by 2030 and beyond requires overcoming substantial technical and economic barriers, including high costs, safety concerns and technical challenges. Advancements in digital solutions can offer promising solutions to those challenges. However, the large-scale deployment of digital solutions in hydrogen systems is in its early stages, with significant technology readiness gaps and regulatory challenges needing to be addressed.

Digital technologies are noticeably lacking in UK hydrogen strategy reports. For example, Hydrogen UK made no mention of digital in its Hydrogen Supply Chain Strategic Assessment[101] and neither the DESNZ Hydrogen Strategy[102] published in 2021, or the Hydrogen Strategy Update to Market: December 2024[103] made any mention of digital technologies either.

Hydrogen as a sector in the UK is in the early stages of development and has not yet had the opportunity to fully incorporate digital operations. AI and digital twins are being adopted by individual companies, but there is a way to go to achieve widespread adoption. Robotics had the least adoption across hydrogen production, utilisation, transportation and storage with no evidence found.

The hydrogen sector is looking at ways to increase the uptake. For instance, the Hydrogen Innovation Initiative (HII) is a collaborative effort aimed at advancing the development and deployment of hydrogen technologies to address pressing energy and environmental challenges. The Digital Catapult is a founding member of HII and aims to unlock the potential of advanced digital technologies in the hydrogen supply chain.[104]. It is establishing a Hydrogen Hub that will serve as a central platform for all hydrogen-related work[105].

There is an appetite for digital service companies to contribute to the hydrogen supply chain. The Scottish Government's report 'A Trading Nation: Realising Scotland's Hydrogen Potential'[106] showed that roughly 80 software and digital service companies are active or potentially looking at activity in the hydrogen supply chain, with around 20 having an active or confirmed interest. This shows the potential for future skills within the industry.

AI is being incorporated into operations across hydrogen production, transportation, storage and utilisation, but at this stage the application of AI is mostly at research or project stage.

High Level Categorisation

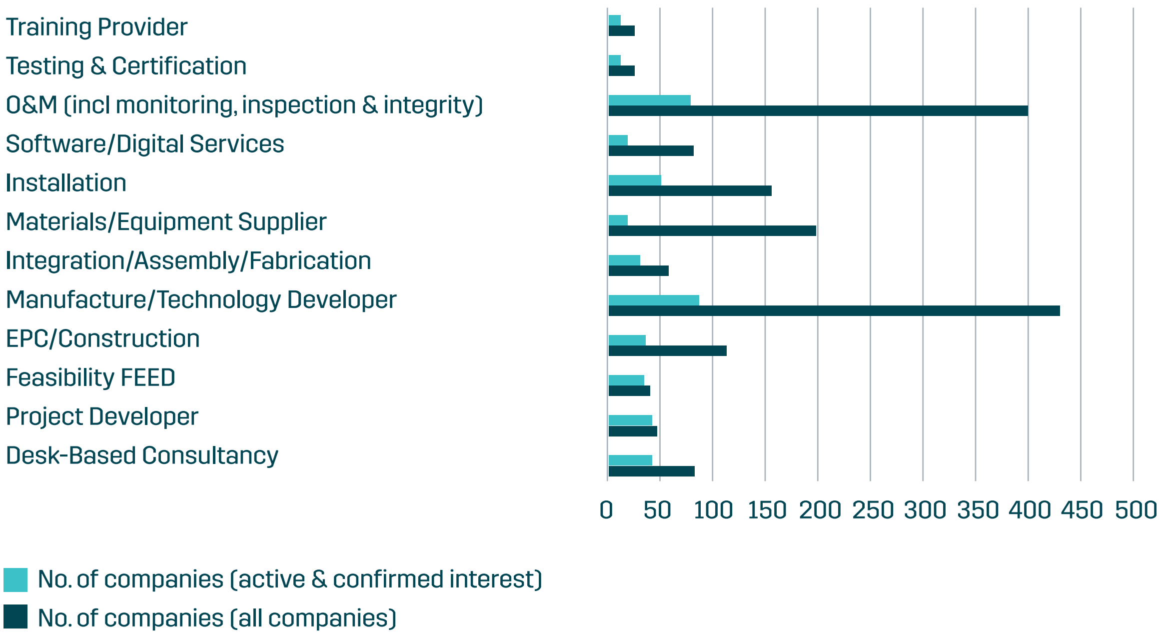

Figure 21 - Scottish Companies active or looking at activity in H2 supply chain (2024)
Source: Scottish Government (2024). 'A Trading Nation: Realising Scotland's Hydrogen Potential - A Plan for Exports'

[101] Hydrogen UK (2024), 'UK Hydrogen Supply Chain Strategic Assessment'
[102] DESNZ (2021, 'UK Hydrogen Strategy'
[103] UK Gov (2024), 'Hydrogen strategy update to the market: December 2024'
[104] Digital Catapult, 'Hydrogen Innovation Programme'
[105] Digital Catapult (2024), 'Everything you need to know about hydrogen technology'
[106] Scottish Government (2024), 'A Trading Nation: Realising Scotland's Hydrogen Potential - A Plan for Exports'

Artificial Intelligence

The UK hydrogen sector is experiencing a significant transition towards decentralisation, decarbonisation, and digitisation. AI/ML technologies are playing a crucial role in this transition by enhancing various aspects of the hydrogen value chain. AI/ML technologies can be used to improve the efficiency and sustainability of hydrogen production, storage, and distribution and to monitor and maintain hydrogen infrastructure, reducing downtime and enhancing safety[107]. Many hydrogen production companies are starting to integrate AI into their operations, but adoption varies across the industry. AI is being incorporated into operations across hydrogen production, transportation and storage, but at this stage the application is mostly at the research or project stage.

Hydrogen	Production		Storage	Transport
	Fuel	Elec	Fuel	Fuel
Artificial Intelligence	3	4	2	2

Table 11 - Hydrogen: Artificial Intelligence Score

Fuel Production

The UK hydrogen energy sector is actively exploring the potential of Artificial Intelligence (AI) to optimise green hydrogen production and enhance the efficiency of energy systems. AI algorithms are being developed to predict power costs and user demand, aiming to optimise hydrogen production and storage, as demonstrated in 2021 by the HyAI project in Orkney, Scotland[108], a collaboration with EMEC and H2GO. HyAI aimed to show how software integrated with hydrogen hardware can make intelligent, data-driven asset management decisions in real time, and optimise renewable energy integration into the UK electricity grid[109] helping Scotland meet its net-zero targets[110].The project included hydrogen production, storage and conversion of hydrogen to power for use in the electricity grid.

Siemens Energy is developing AI tools to help design, engineer and automate hydrogen plants. Their Hydrogen Plant Configurator exemplifies the potential of AI in green hydrogen production and was available to download from the end of 2024[111]. It is an intelligent chatbot based on generative AI, which enables users to create plant designs for hydrogen production.

Electricity Production

In the production of electricity from hydrogen, AI is expected to be applied to the design and development of equipment, but also in the supporting operations and maintenance of production equipment. From research and literature reviews undertaken, there are few examples such as AI is being used is in the material discovery for fuel cell components[112] as well as the use of AI for hydrogen fuel cells[113]. It is noted that ITM Power plans to use Digital twins and AI at its electrolyser manufacturing facility[114].

In 2023, H2GO partnered with RWE for the HyAI4RES project to investigate the use of AI technologies on large-scale power generation facilities, to apply its AI-enabled software management platform (HyAI) on a renewable energy site developed by RWE[115]. The HyAIrRES project received funding in March 2024 to develop an additional module for cases with high seasonal power demand and extreme events[116].

[107] Digital Catapult (2024), 'Digital Solutions for the energy sector'
[108] IRENA, 'Digital backbone for green hydrogen production'
[109] EMEC (2021), 'EMEC and H2GO Power trial AI green hydrogen technology'
[110] Univ Aberdeen (2023), 'AI project aims to supercharge hydrogen production in Scotland'
[111] Siemens (2024), 'Siemens accelerates hydrogen ramp-up with generative artificial intelligence'
[112] Imperial College (2020), 'AI could help improve performance of lithium-ion batteries and fuel cells'
[113] Quintanilla (2025), 'Artificial intelligence and robotics in the hydrogen lifecycle: A systematic review'
[114] ITM Power (2025), 'AI in A Hydrogen Energy Future'
[115] RWE (2023), 'H2GO Power and RWE join forces for innovative hydrogen AI'
[116] DESNZ (2024), 'AI for Decarbonisation Innovation Programme: Stream 2 Projects'

Fuel Storage

The application of AI in UK hydrogen fuel storage is currently in its nascent stages. Research is likely focusing on using AI for predictive maintenance of storage infrastructure and optimising storage operations based on supply and demand forecasts, drawing lessons from applications in the oil and gas sector.

In the UK, hydrogen has an important role to play as an energy storage solution. Current established methods of storing hydrogen are as liquid hydrogen or compression. The 2022 government funded project ShyLO, led by H2GO Power aimed to introduce a new solid-state hydrogen storage solution that could deliver a levelised cost of hydrogen conversion and storage at $0.25/kg by 2028, offering potential savings of up to 55%. The solution is supported by an AI platform, which uses algorithmic prediction of the generation, storage and demand environment. HSSMI intended to lead the scale-up strategy to enable the technology to be rolled out across the UK[117]. The status of the project is unclear.

The UK has one operational large-scale hydrogen storage facility in a salt cavern in Teeside, with operation starting in the 1970s.

Several other projects are in the planning stage. Additionally, hydrogen refuelling stations require hydrogen storage on a smaller scale. There is no evidence found that operational hydrogen storage projects are currently using AI.
In the UK hydrogen transportation is small-scale and commercial operation is unlikely to utilise AI.

Fuel Transport

AI has the potential to be used in the future for optimising hydrogen transmission through pipelines, predicting maintenance needs, and enhancing the safety of transmission networks, drawing parallels with its use in natural gas transmission. Currently, without the infrastructure in place any application will be within the concept design and development.

DNV's FutureGrid project uses AI to develop digital twins to analyse how hydrogen can be integrated into the future energy system[118].

Remote Operations

The hydrogen lifecycle involves complex tasks in hazardous environments. Remote operations are beneficial to hydrogen projects since it can allow real-time data collection, analysis, evaluation and operational control without the need for a physical presence. The continuous monitoring of hydrogen production processes ensures optimal performance and early detection of anomalies, improving efficiency and reducing downtime.

Work is being done to increase reliability and sensitivity of sensors for hydrogen. Digital Catapult's Hydrogen Sensor Accelerator programme is an 8-week programme for five startups engaged in sensor development, within and beyond the hydrogen sector to accelerate the preparedness of sensors for the hydrogen sector and advance the hydrogen supply chain. The programme is part of the Hydrogen Innovation Initiative and is supported by Innovate UK and the Industrial Advisory board[119].

Hydrogen production, storage and transportation can all be carried out remotely.

Hydrogen	Production		Storage	Transport
	Fuel	Elec	Fuel	Fuel
Remote Operations	2	2	2	2

Table 12 - Hydrogen: Remote Operations Score

[117] HSSMI (2022), 'Advancing Solid-State Hydrogen Storage Towards Commercialisation'
[118] DNV (2024), 'Connected Digital Twin Insights'
[119] Digital Catapult, 'Hydrogen Sensor Accelerator Programme'

Fuel Production

Remote operations are being considered for enhancing the efficiency and safety of hydrogen production facilities in the UK, particularly those powered by renewable energy sources. Digital solutions are being explored to enable remote monitoring and diagnostics of hydrogen plants, allowing for quicker identification and resolution of system problems, even in remote locations[120]. The use of augmented reality (AR) tools is also being investigated to support frontline workers in performing inspections and maintenance tasks, with remote expert support available when needed. Furthermore, the development of remotely piloted aircraft powered by hydrogen is underway, potentially enabling remote monitoring and servicing of offshore energy installations.

Remote operations allowed the Dolphyn Hydrogen production project to undertake trials for offshore hydrogen production[121].

Electricity Production

No notable difference is expected between systems that produce hydrogen or those that convert hydrogen to power.

Fuel Storage

Remote monitoring of hydrogen storage facilities is likely being implemented to enhance safety and efficiency, allowing operators to oversee storage conditions and manage operations from a distance. Little evidence was found from literature reviews

Fuel Transport

Remote monitoring of hydrogen transmission pipelines will likely be implemented to ensure the safe and efficient transport of hydrogen, allowing for real-time data collection and analysis from remote locations. Given the early stages of development is it expected that remote operations are being considered but are not yet operational by default.

Digital Twins

Before committing capital, investors require a high level of confidence to reach final investment decision (FID) and want to know which system configuration will optimise their return. From PV to electrolyser capacity, to buffers (such as energy and hydrogen storage), multiple variables must be considered. Digital twins can help clarify project viability by quantifying the impact of external factors on economic performance. Digital twins can model multiple designs and scenarios, including variables such as weather, off-takers demand volatility and local infrastructure (current and future), optimising each design to maximise return on investment and minimise risk.

Production costs have the potential to be reduced by 5-15% through digital twins and supporting interventions[122]. Estimates indicate that digital twin analysis can optimise capital expenditure (CAPEX) by 10-15% whilst reducing risk by 30-50%, along with a marginal change in operating expenditure (OPEX).

Hydrogen	Production		Storage	Transport
	Fuel	Elec	Fuel	Fuel
Digital Twins	4	3	2	2

Table 13 - Hydrogen: Digital Twins Score

[120] Siemens-Energy, 'Green hydrogen production - Siemens Energy'
[121] Dolphyn (2024), 'Our Hydrogen Production Trials'
[122] McKinsey & Company (2024), 'Digital twins: Capturing value from renewable hydrogen megaprojects'

Fuel Production

BOC (part of the Linde Group) is the largest supplier of hydrogen in the UK and operates the largest independent hydrogen production plant in the UK, supplying industries via a dedicated pipeline[123] as well as hydrogen refuelling stations. Digital technologies are incorporated into Linde's operations where digital twins support the plant engineering process and for remote diagnostics[124].

H2GO Power's AI-powered software platform uses optimisation algorithms to create a customised digital twin for each site to optimise design and operation of hydrogen systems. At project development stage it provides a systematic and data-driven approach to infrastructure sizing, technology selection and project financing. Once operational, it integrates with, and controls, the assets via a hydrogen-native management system[125]. Unfortunately, H2GO went into administration in August 2024, and it is unclear of the status of the project.

Electricity Production

ITM Power who manufacture electrolysers are incorporating digital twins into their operations[126].

Fuel Storage

Mathematical models of hydrogen-based energy storage systems (HESS), including electrolysers, fuel cells, and storage tanks, are being developed for power systems dynamic simulation studies, such as providing ancillary services to the grid[127]. These modelling efforts are essential for ensuring the efficient and reliable operation of hydrogen production and storage facilities, as well as their integration into the broader energy system. This includes modelling the behaviour of hydrogen under different storage conditions, assessing the safety of storage solutions, and optimising storage capacity and operational parameters.

Digital twins are being explored for large-scale hydrogen storage solutions in the UK, particularly for salt cavern storage. Research aims to leverage digital twins to evaluate and forecast hydrogen leaks by incorporating real-time and historical data from sensors, geological information, and environmental factors, as demonstrated by SSE's Aldbrough Hydrogen Pathfinder project[128].

Fuel Transport

Digital twin technology is emerging as a valuable tool for managing the complexities associated with the development and deployment of hydrogen systems in the UK. DNV has worked with National Gas on the FutureGrid project to analyse integration of hydrogen into the National Transmission System. It uses a demonstrator digital twin to explore and understand how hydrogen can be transported and stored safely and its role in the future energy system[129]. National Gas is exploring the potential of digital twins to manage the introduction of hydrogen into existing gas networks, with the FutureGrid test facility in Cumbria serving as a key project in this area[130].

The SHAPE UK project is utilising digital twins to optimise operations within Portsmouth International Port as part of a green hydrogen system demonstration . These efforts highlight the recognition of digital twins as a robust solution for managing the integration of hydrogen into the UK's energy infrastructure.

Digital twins are being considered for managing hydrogen transmission networks in the UK, allowing for the simulation of hydrogen flow, the assessment of pipeline integrity, and the optimisation of network operations as the infrastructure develops[132].

These tools are vital for understanding the implications of transporting hydrogen through existing natural gas pipelines in the UK. Studies are using software to model the UK high-pressure gas network and analyse the effects of hydrogen injection on pressure levels, linepack, and compressor energy consumption. Other tools enable modelling of hydrogen transport scenarios, including pipeline transport and blending with natural gas.

[123] Haush (2025), 'Hydrogen Gas in the UK: Supply, Quantities and Costs'
[124] Linde (2024), 'Turning Big Data into Operational Insights'
[125] Joshua Ivanhoe, H2GO Power (2023), 'Seeking US-based organisations to demonstrate the impact of HyAI on your hydrogen projects'
[126] ITM Power (2021), 'Hydrogen and Energy Storage'
[127] Univ of Cardiff (2023), 'Modelling and Simulation of a Hydrogen-Based Energy Storage System'
[128] ASME (2024), 'Leveraging Digital Twins for Hydrogen Loss Mitigation in Large Scale Salt Cavern Hydrogen Storage'
[129] DNV (2024), 'Connected Digital Twin Insights'
[130] DNV (2024), 'National Gas explores the potential of digital twins to manage complexity in the energy transition'
[131] Energy Digital (2021), 'IOTICS to create digital twin in Portsmouth hydrogen project | Energy Magazine'
[132] DNV (2024), 'Leveraging a network of safe, integrated digital twins to address the energy challenge

Robotics and Autonomous Systems

The hydrogen lifecycle involves complex tasks in hazardous environments. The integration of robotics offers a solution to improve efficiency, precision safety and scalability. Robotics is used alongside AI driven predictive algorithms to minimise downtime in hydrogen production. They can also be used to manage high-pressure storage tanks or to handle cryogenic storage procedures. In transportation and storage, the application of robotics is mainly conceptual, focusing on inspection or visualisation through digital twins[133]. No evidence of the use of robots for hydrogen was found in the UK.

Fuel Production

Robotics and autonomous systems are in the early stages of exploration and adoption within the UK hydrogen industry, primarily focused on enhancing manufacturing processes and enabling autonomous maritime applications.

Also, ABB have developed robots focused on hydrogen fuel cell stack lines and hydrogen tank manufacturing lines[134]. ABB has headquarters in the UK but doesn't yet provide robots for the hydrogen sector.

A UK startup has received approval in principle for its autonomous surface vessel powered by liquid hydrogen, designed for offshore security monitoring and data collection, indicating a potential future role for autonomous systems in the hydrogen sector[135].

These initiatives suggest a growing recognition of the potential for robotics and automation to improve efficiency and safety across the hydrogen value chain.

Electricity Production

The University of Sheffield AMRC is involved in projects aimed at de-risking the assembly and production scale-up of hydrogen fuel cells for various transport sectors using collaborative robots and Industry 4.0 technologies[136]. Also, within manufacturing, the ITM Power Bessemer Park 'Gigafactory' (Sheffield, UK) is equipped with machines to automate electrolyser stack production[137,138]. The electrolysers ITM sells are autonomous.

Fuel Storage

The use of robotics in hydrogen storage is likely focused on automated inspection and maintenance of storage tanks and related equipment, drawing from experiences in other sectors with similar infrastructure.

Fuel Transport

Robotics are expected to play a role in the inspection and maintenance of hydrogen transmission pipelines in the UK, similar to their application in natural gas pipelines, ensuring network integrity and safety

Hydrogen	Production		Storage	Transport
	Fuel	Elec	Fuel	Fuel
Robotics and Autonomous Systems	3	3	2	2

Table 14 - Hydrogen: Robotics and Autonomous Systems Score

[133] Quintanilla (2025), 'Artificial intelligence and robotics in the hydrogen lifecycle: A systematic review'
[134] ABB, 'Hydrogen'
[135] Acua Ocean (2024), 'How Will This Autonomous Vessel Decarbonise The Maritime Sector'
[136] AMRC (2021), 'Fuelling a green future with hydrogen electric'
[137] Renewables Now (2021), 'Interview - ITM Power fully funded to build 2nd gigawatt-scale factory'
[138] DBEIS (2021), 'Gigastack Phase 2: Pioneering UK Renewable Hydrogen'

Cybersecurity

Cybersecurity is an increasingly important consideration for the developing UK hydrogen sector, particularly as hydrogen production, storage, and transmission become more integrated with digital control systems[139]. In 2023 alone, 90% of the world's largest energy companies suffered cybersecurity breaches, with critical infrastructure becoming a primary target for state-sponsored hackers and cybercriminals. According to the UK Government Cybersecurity Breaches Survey 2024[140], over 50% of UK businesses experienced a cyber breach or attack in the past year, and over 75% now consider cybersecurity their top priority.

The energy sector, including emerging areas like hydrogen, is a target for cyberattacks, making it essential for hydrogen companies to implement robust cybersecurity frameworks to protect their operations and infrastructure[68]. This includes measures to secure digital control systems, protect sensitive data, and ensure the resilience of hydrogen supply chains against cyber threats and to ensure the integrity and reliability of hydrogen systems, prevent disruptions, maintain safe operations, and prevent physical damage or operational failures.

As operators of hydrogen production, storage, and transmission are identified as critical entities under the Critical Entities Resilience (CER) Directive[141], compliance with cybersecurity requirements is becoming mandatory. These regulations require robust cybersecurity measures for hydrogen production, transportation and storage.

Given the current status of deployment of hydrogen-related assets, the adoption of cybersecurity-related technology is expected to be similar to that of Fossil-Fuel (Oil and Gas) industry, however not widespread given the maturity of the technology and capital assets. On this basis a score of (5) is expected at all levels.

Hydrogen	Production		Storage	Transport
	Fuel	Elec	Fuel	Fuel
Cybersecurity	5	5	4	4

Table 15 - Hydrogen: Cybersecurity Score

[139] RenewableUK (2025), 'Growing cybersecurity threats in the energy sector and how businesses stay resilient'
[140] UK Gov (2024), 'UK Government Cybersecurity Breaches Survey 2024'
[141] Critical Entities Resilience Directive

Summary and Overall Scoring

Digital adoption within the hydrogen space is in stark contrast to fossil fuels. Although influenced by oil and gas knowledge and experience, the maturity of the sector, together with challenging economic conditions and low levels of asset deployment, has indicated a generally low level of adoption as seen in Section 34.

Slightly higher adoption of AI was seen in the conversion of hydrogen to electricity (e.g. fuel cells) than in the production/generation of hydrogen (e.g. electrolyser), but this variation is not expected to be significant. Hydrogen storage and transport were regarded as having similar, low adoption rates.

Remote operations and robotics have not featured highly, primarily due to the low maturity of asset deployment. This is an area of opportunity, as both should be considered within the conceptual design of new assets.

The scoring reflects the current understanding of digital technology application within the hydrogen sector. This is echoed by external research[142] which highlights the huge potential that is available, however many digital technologies are not being considered. With storage and transportation of hydrogen still in the earlier stages of development, cybersecurity adoption is expected to be less widely adopted.

Digital adoption within the hydrogen space is in stark contrast to fossil fuels.

Hydrogen	Production		Storage	Transport
	Fuel	Elec	Fuel	Fuel
Artificial Intelligence	3	4	2	2
Remote Operations	2	2	2	2
Digital Twins	4	3	2	2
Robotics and Autonomous Systems	3	3	2	2
Cybersecurity	5	5	4	4

Table 16 - Hydrogen: Overall scoring

[142] Brunel University (2025), 'Artificial intelligence and robotics in the hydrogen lifecycle: A systematic review'

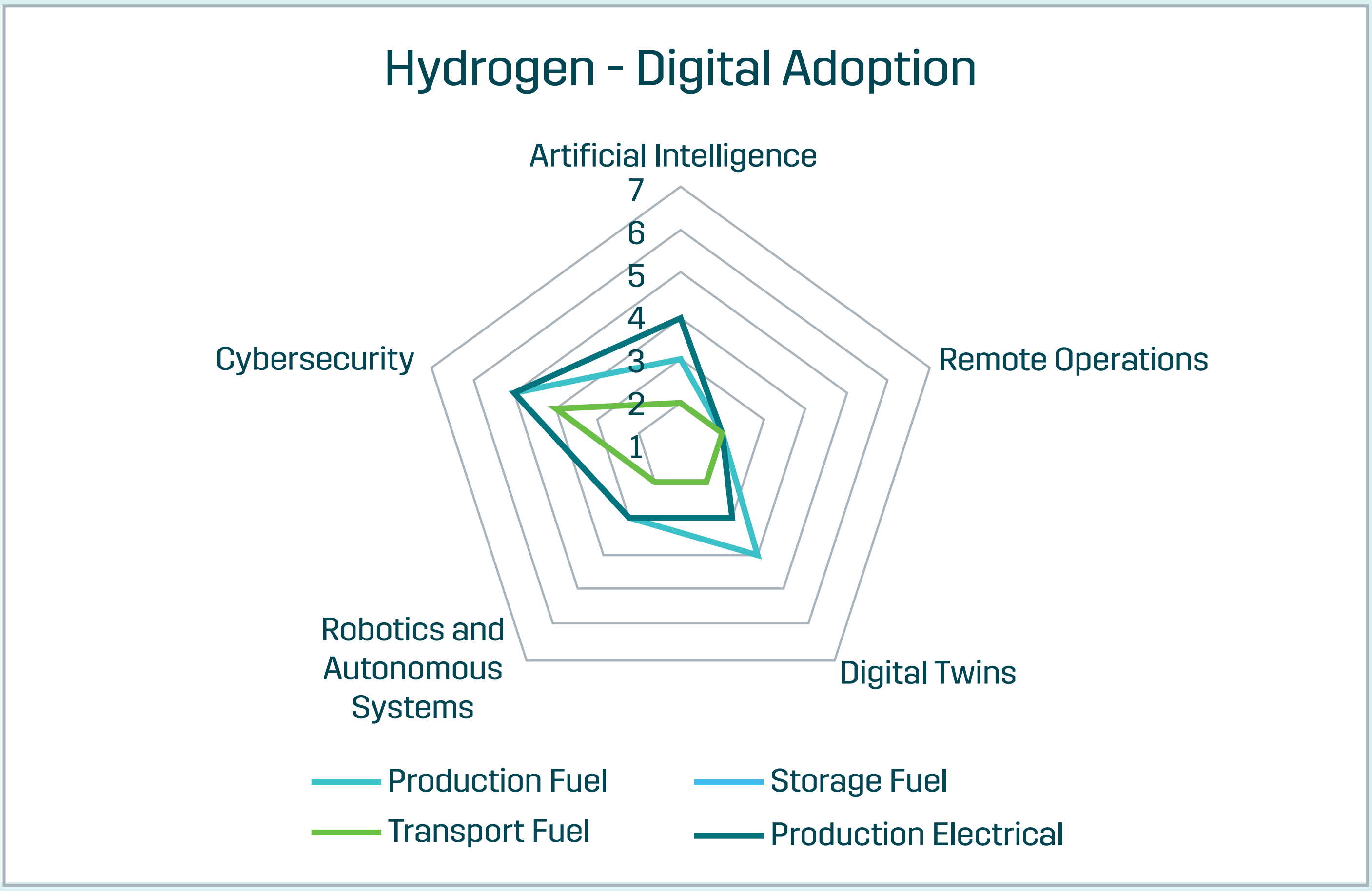

Figure 22 - Hydrogen Scoring

Challenges within the hydrogen lifecycles have been identified as:

- data challenges persist, as many AI models lack high-quality, standardised datasets
- scalability concerns exist, as AI-driven hydrogen optimisation models often perform well in small-scale demonstrations but struggle when applied to industrial-scale operations
- integration bottlenecks remain a hurdle, as the convergence of AI, robotics, and IoT has limited real-world deployment
- Gaps exist in robotics applications, especially in hydrogen handling, transport automation, and infrastructure maintenance, even with the successful implementation of digital twins and automated inspection systems in hydrogen pipelines and storage.

There is wider recognition that digital technology is core to the future hydrogen infrastructure[143]; the challenge is that of overcoming the barriers to adoption that are partly legacy (from oil and gas) and partly driven by pressure to deploy infrastructure.

[143] IRENA (2024, 'Digital backbone for green hydrogen production'

35. Nuclear

The nuclear sector is very mature and is driven by safety, reduced risk and reliability. Given the significant investments and national security interests in the area, the nuclear industry has applied digital technologies in many areas because of the stringent need to understand and ensure safety above all else. Digital technologies have been used to simulate reactor behaviour and inform and to improve reactor design, performance, safety and operation. However, given the timescales for construction and build, the nuclear sector can equally be slow to implement new technologies, as system safety is paramount.

The UK government has given nuclear power plants critical infrastructure status and is now pushing for the co-location of data centres and nuclear. Planning reforms have allowed nuclear sites to be constructed anywhere in England and Wales, as well as enabling an easier path to build Small Modular Reactors. This is driving a surge in funding and research for digital technologies in the nuclear sector.

There is a large focus on AI and robotics to carry out remote operations and reduce the requirement for people in hazardous environments. Continuous sensor monitoring and analysis are important at nuclear facilities to ensure the conditions are optimal and to ensure safety. Robots are often used at decommissioning sites to carry out inspections and to support decontamination plans. Notably, the world's first remote operations from an offsite location of a robot at a nuclear facility occurred at the Sellafield decommissioning site in the UK in March 2025[144].

EDF - the operator of the UK's fleet of nuclear power stations - is part of a team developing digital twin technology to monitor the condition of components of nuclear power plants.

Artificial Intelligence

Regulatory approval needs to be in place before AI/ML can be implemented. In 2024, the Office for Nuclear Regulation (ONR) released a paper outlining its approach to regulating AI in the nuclear sector[145], and how it aligns with HMG principles-based framework. They are actively looking to strengthen their regulatory arrangements, working with duty holders who are considering the deployment of AI on nuclear sites.

AI/ML can be used to improve safety and security, on site health and safety, safeguards and the transport of nuclear and radioactive materials. Mentions of AI are often intertwined with the use of robotics with activities such as inspection, handling and decommissioning. In 2017 the Robotics and Artificial Intelligence for Nuclear (RAIN) Hub[146] was set up to carry out research, enhance connectivity between research and industry, and improve and deploy robotics and artificial intelligence in nuclear. The project had 5 working groups: AI and robotics in remote inspection, handling, human robotic interaction, standardisation and verification and autonomy.

In April 2022, the Robotics and Artificial Intelligence Collaboration (RAICo) began[147]. This is a collaboration between the UKAEA, NDA, Sellafield Ltd and the University of Manchester with a focus on remote handling, size reduction, robotics and AI data, and digital infrastructure. The programme aimed to develop capabilities to deploy robotics and AI technologies for safer, faster and more cost-effective decommissioning in fusion engineering.

In April 2025, DESNZ announced £20 million of funding[148] for 'Starmaker One' - a British private fusion investment fund to help fusion businesses and start-ups in the sector grow and commercialise at scale. The funding includes support to companies to develop technologies and capitalise on the opportunities of fusion energy in markets including industrial AI and robotics.

AI has become an integral part of nuclear fusion, reducing the time simulations take from hours to less than a second. If nuclear fusion is to become a major source of energy in the future, AI will play an important role, especially as AI will develop before nuclear fusion is commercialised[149].

With the Nuclear Sector, for the purposes of this report, consideration is only given to the use of digital technology in the production of energy as well as the storage of nuclear waste (the fuel). These are scored in the sections below and summarised in the accompanying tables.

[144] World Nuclear News (March 2025), 'Remotely operated robot deployed at Sellafield'
[145] Office for Nuclear Regulation (ONR) (2024), 'ONR's pro-innovation approach to AI regulation'
[146] Robotics and AI in Nuclear (RAIN)
[147] UK Atomic Energy Authority, 'RAICo: Robotics and AI Collaboration'
[148] DESNZ (2025), 'Government kickstarts £100 million fusion investment'
[149] IEA (2025), 'The State of Energy Innovation'

Nuclear	Production	Storage
	Elec	Fuel
Artificial Intelligence	5	5

Table 17 - Nuclear: Artificial Intelligence Score

Electricity Production

The United Kingdom is at the forefront of integrating artificial intelligence (AI) into its nuclear sector, with applications spanning from operational optimisation to predictive maintenance. AI technologies are being deployed across the UK nuclear industry to enhance safety, efficiency, and sustainability in energy production.

For example, EDF Energy has implemented AI for real-time condition monitoring and predictive maintenance, using an AI solution called Metroscope, which utilises "digital twins" to optimise maintenance work in nuclear plants[150].

Fuel Storage

Sellafield, one of the UK's most important nuclear sites, has partnered with Ada Mode to develop predictive maintenance solutions for its nuclear waste processing facilities[151]. This proof-of-concept project aims to establish a site-wide predictive maintenance capability that could transform how the entire Sellafield complex operates. The initiative focuses on increasing the reliability of facilities through AI adoption, particularly at the strategically important Waste Vitrification Plant (WVP).

Given the safety implications use of data monitoring and anomaly detection will be common practice.

Remote Operations

The use of remote operation in nuclear is becoming more common, particularly for decommissioning. In decommissioning, remote operations help clear radioactive waste, enhancing safety and efficiency. Remote operation is also being used for maintenance and inspection. Nuclear power plants also contain technology enabling continuous remote monitoring such as sensors, cameras and AI to track critical parameters, ensuring safety and optimal performance.

The UKAEA has announced £3.5m total to 13 organisations to develop robust sensing technologies for use in future fusion power plants. These organisations will now undertake technical feasibility studies, taking their sensing and diagnostics technologies to 'proof of concept' stages[152].

Nuclear	Production	Storage
	Elec	Fuel
Remote operations	3	5

Table 18 - Nuclear: Remote Operations Score

150 Energy Monitor (2022), 'French utility EDF centres innovation strategy on AI and blockchain'
151 Ada Mode, 'Predictive Maintenance for Nuclear Decommissioning'
152 UK Atomic Energy Authority (UKAEA) (2025) 'Creating sensors for extreme fusion energy conditions'

Electricity Production

Remote operation of nuclear facilities isn't generally needed and wouldn't be permitted from a cybersecurity perspective. However, remote operation of some of the supporting elements of a nuclear facility is commonplace, e.g. robotics

Fuel Storage

Sellafield is the home to the vast majority of the UK's radioactive nuclear waste storage. Remote operations have been noted as applying primarily to monitoring of facilities but also remote operation of robotic systems.

Sellafield alongside AtkinsRealis deployed a customised Boston Dynamics Sport Quadrupedal Robotic 'dog' to undertake various tasks including data gathering and clean-up work[153]. The UK's Sellafield nuclear site achieved an industry first in March 2025 by successfully operating a robot remotely from an off-site location to help clear radioactive waste from a nuclear waste site.

AtkinsRealis and Sellafield Ltd's remote technology group worked closely to put in place the necessary digital and cyber protocols to enable the safe and secure operation to allow remote operation. The robotic 'dog' can be operated remotely, to enhance safety, efficiency, and decision-making on nuclear-licensed sites. Robot dogs are not yet being operated remotely from offsite locations on nuclear production sites, but this demonstrates the potential for virtual operation of nuclear production sites in the future.

Digital Twins

Digital twins can simulate different operational scenarios, allowing operators to predict and mitigate potential issues before they occur, resulting in enhanced operation and increased safety and efficiency. They can also be used in the design phase to identify potential issues early leading to more robust and reliable designs. Through predictive analytics, digital twins can identify and address potential failures before they occur reducing downtime. With safety a key consideration for nuclear, digital twins can simulate emergency scenarios and assess the impact of different safety measures to inform safety protocols and risk management strategies.

From a construction perspective, digital twins and 4D planning/ BIM tools are being used to streamline decision-making. The Integrated Nuclear Digital Environment (INDE) project estimates its digital twins could result in a 20% reduction in construction costs[154].

Synergistic utilisation of Informatics and Data Centric Integrity engineering (SINDRI) is a 5-year project that started in 2021 that is developing digital twin technology to monitor the condition of components of nuclear power plants[155]. The project is led by the University of Bristol-led team and includes EDF (who operate all UK nuclear power stations currently generating power). The project will enable the team to develop an overarching digital framework that encompasses a suite of models that simulate the behaviour of materials through their lifecycle. The framework will be incorporated into EDF's federated simulation ecosystem of multi-physics digital twins, replacing current manual processes.

The National Nuclear Laboratory[156] provides a capability catalogue[157] for the modelling and simulation tools throughout the nuclear fuel cycle available to UK consumers, including the UK government. These include structural and thermal modelling, chemical and process modelling, and software development/ inventory management. All of these modelling tools can be considered as digital twin components.

Nuclear	Production	Storage
	Elec	Fuel
Digital Twins	6	4

Table 19 - Nuclear: Digital Twins Score

[153] Nuclear Decommissioning Authority (2025), 'Sellafield Ltd and AtkinsRealis reach new robotics milestone
[154] Integrated Digital Nuclear Design Programme (2019), 'Integrated Nuclear Digital Environment'
[155] EDF - Digital twins to monitor nuclear plant structures
[156] NNL, 'National Nuclear Laboratory'
[157] NNL, 'NNL Capability Catalogue'

Electricity Production

In sectors such as nuclear fusion, digital twins are helping design and test equipment and in the development of small modular nuclear fission reactor designs[158].

The UK Atomic Energy Authority (UKAEA) is developing an ambitious "industrial metaverse" to simulate processes in a nuclear fusion reactor[159]. This project, in collaboration with Cambridge University, Intel and Dell, aims to create a comprehensive digital twin to accelerate the development of fusion power. UKAEA's goal is to have a fully functioning fusion power plant providing electricity to the grid by 2040, and digital twins are critical to achieving this timeline.

Digital tools, simulation and modelling have been core to the nuclear industry for many years, given the complexity, the need for safety, reliability and reduction of risk, this sector naturally scores highly.[160]

Fuel Storage

In the coming years, nuclear decommissioning will become a more and more relevant activity, as most of the 400+ nuclear power plants all over the world are 40-50 years old. This implies that new radiation/waste storage sites will have to be put in operation with consequent increasing needs of safety and security. The potential for enhance monitoring and visualisation of data is huge. Whilst fairly specialised in application some examples do exist but are early stage.

Research led by the University of Manchester and others is exploring the development of a digital twin for the UK's planned Geological Disposal Facility (GDF)[161].

Robotics and Autonomous Systems

Robots are employed to handle hazardous materials, perform inspections, and maintain systems. Globally around 30% of routine inspections in nuclear power plants are performed by robots[162]. In the UK, the Nuclear Decommissioning Authority's (NDA) is aiming to half the number of high hazard decommissioning activities carried out by humans by 2030[163].

It is clear therefore that robotics play a critical and growing role within the nuclear sector and scoring reflects that.

Nuclear	Production	Storage
	Elec	Fuel
Robotics and Autonomous Systems	6	4

Table 20 - Nuclear: Robots and Autonomous Systems Score

[158] IEA (2025), 'The State of Energy Innovation'
[159] Computing (2023), 'UKAEA Unveils Plan for Digital Twin for Nuclear Fusion Reactor'
[160] I Nistor (Head of Nuclear R&D, EDF),'Nuclear Digital Twins at EDF - quick overview'
[161] K Bartha, Univ Manchester (2021), 'Potential Role of Digital Twins in the Geological Disposal Facility Project'
[162] 3 Laws, 'Robot Autonomy and the Future of Nuclear Electric Power Generation'
[163] ONR (2023), 'Innovative use of robots and unmanned aerial vehicles at Sellafield'

Electricity Production

The robot dog at the Sellafield site has been used since November 2023 to carry out inspections and create future clean-up plans. The robot uses a light detection and ranging laser scanning system (LiDAR)[164].

The use of robotics for nuclear power is a focus of funding and innovation. EPSRC has funded the Hot Robotics Facility[165] where robots and test spaces can be hired for nuclear research by academics, SMEs and industry. The facility comprises of equipment to develop, test and demonstrate robotic solutions for nuclear, allowing low TRL robotics research to progress to TRL 6/7.

In 2017 the Robotics and Artificial Intelligence for Nuclear (RAIN) Hub[166] was set up to carry out research, enhance connectivity between research and industry, and improve and deploy robotics and artificial intelligence in nuclear.

Fuel Storage

In April 2022, the Robotics and Artificial Intelligence Collaboration (RAICo) began[167]. This is a collaboration between the UKAEA, NDA, Sellafield Ltd and the University of Manchester with a focus on remote handling, size reduction, robotics and AI data, and digital infrastructure. The programme aimed to develop capabilities to deploy robotics and AI technologies for safer, faster and more cost-effective decommissioning in fusion engineering.

The Office for Nuclear Regulation (ONR) will take part in a five-year UKRI funded project alongside universities, nuclear site licensees and other regulators, focusing on the development of robotics for the UK nuclear industry and how to structure associated safety arguments. The UK Atomic Energy Authority (UKAEA) is leading the creation of a new £4.9m nuclear robotics and AI cluster across Cumbria and Oxfordshire. The cluster will accelerate the decommissioning of the UK's legacy nuclear fission facilities and keep people out of hazardous environments[168].

Cybersecurity

Cybersecurity is a core strength in the civil nuclear infrastructure as any breach could result in theft of sensitive information, a reduction in the reliability of energy production, damage to infrastructure, or the release of radiation. These have significant repercussions to the facility and to national security.

Due to the very clear risks relating to nuclear, cybersecurity assurance is paramount. In 2022, the UK government published the Civil Nuclear Cybersecurity Strategy[169] setting goals to secure nuclear infrastructure by 2026.

Key objectives include:

- Prioritising cybersecurity within risk management frameworks
- Proactive mitigation of cyber risks across IT and OT systems
- Enhancing resilience through incident preparedness and response
- Sector-wide collaboration to increase cyber maturity and skills

Underpinning this strategy is an overlapping regime of cybersecurity laws such as the Nuclear Industries Security Regulations 2003[170] and The Network of Information and Security Regulations[171].

Whilst the strategy is being implemented there are gaps in the cybersecurity of UK nuclear sites. Many plants are outdated. Cybersecurity regulations have existed in various forms over the years, but there is increasing activity by regulators to strictly enforce them. The ONR repeatedly found gaps in Sellafield's cybersecurity from 2019 to 2023 that could not be fully resolved[172] and has been prosecuted for cybersecurity breaches[173].

Three priorities for the UK.[174]

- Speed up the implementation of the cybersecurity strategy.
- Consider cybersecurity from the design stage of SMRs
- Better connect work on the cybersecurity of nuclear infrastructure with other UK government cybersecurity efforts

Sector-wide, the UK is accelerating its efforts to ensure both types of facilities achieve robust, resilient, and modern cybersecurity standards, with full implementation of strategic objectives targeted for 2026-2027.

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164 BBC News (2023), 'Sellafield nuclear waste clear up helped by robotic rob'
165 United Kingdom National Nuclear Laboratory, 'Hot Robotics'
166 Robotics and AI in Nuclear (RAIN)
167 UK Atomic Energy Authority, 'RAICo: Robotics and AI Collaboration'
168 UKAEA (2024), 'UKAEA to lead the creation of a nuclear robotics and AI cluster linking Cumbria and Oxfordshire'
169 UK Gov (2022), 'Civil Nuclear Cyber Security Strategy 2022'
170 Legislation Gov (2003),'Nuclear Industries Security Regulations 2003'
171 The National Law Review (2025), 'Cybersecurity in the Nuclear Industry: US and UK Regulation and the Sellafield Case'
172 Chatham House (2024), 'The UK needs to move faster on nuclear and energy cybersecurity'
173 The National Law Review (2025), 'Cybersecurity in the Nuclear Industry: US and UK Regulation and the Sellafield Case'
174 Chatham House (2024), 'The UK needs to move faster on nuclear and energy cybersecurity'

Electricity Production

While not immune to cyber threats, UK nuclear power plants for electricity generation have not experienced the same level of recent, publicised cybersecurity breaches as waste storage sites. Regulatory frameworks and sector strategies have driven a higher baseline of cyber resilience, especially as new reactors are planned and constructed.

Power production plants maintain a high level of cybersecurity maturity, driven by the criticality of continuous, safe energy production and the integration of cyber risk into broader safety management systems.

Fuel Storage

Waste storage and decommissioning sites have historically lagged behind power production sites in cybersecurity adoption, as evidenced by the Sellafield case and subsequent regulatory action. The gap is narrowing rapidly due to increased regulatory scrutiny, sector-wide strategies, and major new investments in cybersecurity infrastructure, particularly for legacy and waste sites.

The most prominent example, Sellafield, which manages nuclear waste and decommissioning, has faced significant cybersecurity failings between 2019 and 2023. Investigations revealed major vulnerabilities, including exposed sensitive information and inadequate protection of IT systems[175]. Sellafield pleaded guilty to criminal charges, resulting in regulatory fines and enhanced oversight by the Office for Nuclear Regulation (ONR).

In response to these failures, the Nuclear Decommissioning Authority (NDA) has launched new cybersecurity initiatives, such as the Group Cyberspace Collaboration Centre (GCCC) in Cumbria, to accelerate the adoption of advanced cyber protections across all 17 legacy nuclear sites.

Nuclear	Production	Storage
	Elec	Fuel
Cybersecurity	6	5

Table 21 - Nuclear: Cybersecurity Score

[175] National Security News (2024), 'UK nuclear plant cyber failures expose national security risk'

Summary and Overall Scoring

Section 35 shows that the analysis of the nuclear sector highlighted a high level of adoption across all digital technologies for electrical production use cases, i.e. power. Although AI is understood to be used heavily within the design, operations and maintenance, it is not expected to be widespread in its application. For nuclear power plants, remote operations are not expected to feature highly given the primary need to manage the operation in-person, let alone the considerable cybersecurity concerns relating to remote operations.

Nuclear (waste) storage was considered and a reasonably mature level of adoption of technology was found; slightly lower adoption of robotics and digital twins, although that is expected to be on the rise.

Nuclear	Production	Storage
	Elec	Fuel
Artificial Intelligence	5	5
Remote Operations	3	5
Digital Twins	6	4
Robotics and Autonomous Systems	6	4
Cybersecurity	6	5

Table 22 - Nuclear: Overall scoring

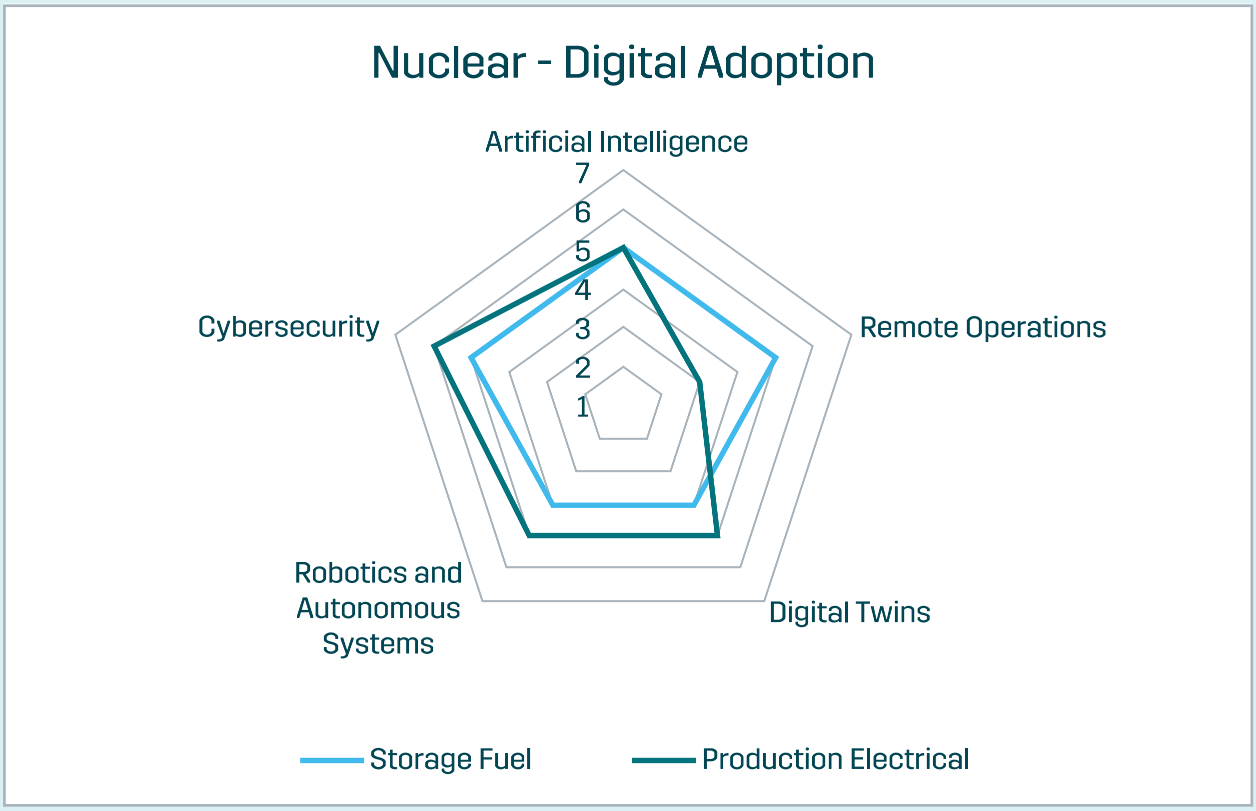

Figure 23 - Nuclear Fuels Scoring

36. Solar

In 2022, distributed PV represented 48% of global solar PV capacity additions, and deployment is rising rapidly. Increased distributed solar increases the complexity of managing power flows and maintaining the stability of the power system, particularly for electricity distribution. Digitalised grids and digital tools can alleviate the challenges of managing an increasingly distributed grid, whilst fostering greater system efficiency[176].

UK homes are installing solar panels to cut energy bills. AI enables smart homes to manage energy generation and consumption remotely, including EV charging and appliance usage during high generation or low electricity prices. Smart meters are common, and intelligent solar setups may become standard soon. For solar farms, AI/ML can optimise battery charging and discharging to increase profits.

Prior to installation, solar farms will carry out modelling and simulation to predict generation, determine the optimum configuration and design of the solar panels. Once installed, solar farms are continual monitored and remotely controlled to optimise generation.

At a small scale there was no evidence of the use of digital twins for solar on its own. However, the Energy System Digital Twin will create an Integrated Energy System-Digital Twin for a future multi-vector energy system, including solar. Robotics aren't being used for distributed PV. However, researchers are looking into the use of robotics for installing and maintaining solar farms.

There are many points of connection from solar to the grid and it is often connected to household devices, making it easier for hackers. Cybersecurity for solar is covered by various regulations. The Network and Information Systems (NIS) Regulations 2018[177] applies to larger solar farms, whilst the UK Product Security and Telecommunications Infrastructure (PSTI) Regime[178] requires all manufacturers of interconnected devices meet basic cybersecurity devices. There are multiple organisations that are providing solar services to solar farms in the UK.

Only the digital technologies related to electrical production will be considered.

Artificial Intelligence

AI is being utilised across the solar industry to increase efficiency and reduce costs and can be used to optimise the positioning of solar panels to maximise solar production. AI-based predictive analytics can identify potential issues with solar panels or inverters before major problems occur. AI is increasingly being used in the integration of solar systems with smart grids and can automatically adjust, or be used to encourage, energy consumption based on real-time weather conditions and grid demand[179].

In 2019, the National Grid Electricity System Operator partnered with the Alan Turing institute to use machine learning to refine forecasts for solar and wind energy, resulting in an improvement of 33% in solar forecasts[180].

In the UK AI is helping grid operators balance supply more efficiently. Utilities are also deploying smart inverters and battery management systems that use machine learning to optimise charging, discharging and bidding into grid service markets[181]. Smart homes are an enabler for AI-driven solutions for solar PV, providing the data required to manage energy generation and consumption in a smarter and more flexible way. This includes predicting sunlight patterns, integrating with smart home devices and automatically diverting excess energy to high-usage appliances. Smart meters are already widespread in the UK, but intelligent solar setups could soon become standard[182].

Given widespread use of AI in the operation of solar, a high score is applied.

Solar	Production
	Electrical
Artificial Intelligence	6

Table 23 - Solar: Artificial Intelligence Score

[176] IEA (2023), 'Digital tools will help keep distributed solar PV growing strongly'
[177] NIS (2023), 'The NIS Regulations 2018'
[178] UK Gov (2024),'The UK Product Security and Telecommunications Infrastructure (Product Security) regime'
[179] Omdena (2023), 'Top 10 AI Innovations in the Solar Industry of 2024'
[180] AI Innovation for Decarbonisation's Virtual Centre of Excellence (ADViCE), 'AI for decarbonisation'
[181] Nimbus (2025), 'UK Solar and energy storage market report 2025'
[182] NCS (2025), '7 Game-Changing Solar PV Panel Technology Trends for the Future in the UK'

Remote Operations

Smart inverters can automatically adjust output to maintain grid stability supporting voltage and frequency control, reduce energy losses, enable granular management of resources, and enable more effective identification of faults and subsequent service restoration. Remote monitoring and diagnostics tools can enable predictive maintenance, allowing businesses to proactively identify potential issues before they occur resulting in reduced downtime.

Once a solar panel is installed there is minimal labour required for operation. Remote operations are therefore focused on monitoring. For example, Natural Generation, one of the leading renewable energy companies in the South West, provides remote continual remote monitoring and remote plant control for utility scale solar farms, to optimise generation and maximise return[183].

Given the maturity in the industry and the fundamental requirement for remote monitoring. A high score is proposed.

Solar	Production
	Electrical
Remote Operations	6

Table 24 - Solar: Remote Operations Score

Digital Twins

On a national basis, the Energy System Digital Twin project is a 4-year project that will create an Integrated Energy System-Digital Twin for a future multi-vector energy system. Energy vectors in the future energy system include wind, solar, tidal, geothermal, hydrogen and electrified transport and heating. Digital twins will play a key role in designing and operating these future systems[184].

Digital twins can provide sophisticated forecasting tools to help predict weather patterns, and how much electricity is produced and consumed from PV locally. Equally, it is often the case that modelling is performed prior to confirming the location of solar farms, to ensure that environment conditions are maximised to drive optimal performance.

It is expected digital twins are used for day-to-day comparison of each solar panels detailed performance criteria, however the detail does not need to be comparable to more complex systems.

Solar	Production
	Electrical
Digital Twins	4

Table 25 - Solar: Digital Twins Score

[183] Natural Generation, 'Solar PV Operations and Maintenance'
[184] University of Strathclyde (2023), 'Digital twin' project will inform future innovation in the UK energy industry'

Robotics and Autonomous Systems

Offshore wind will need to increase sevenfold, necessitating operations in deeper, more remote waters. Robotics and Autonomous Systems (RAS) are crucial for the future of O&M in offshore wind farms and can lead to significant improvements in efficiency and safety by reducing the need for human intervention. Current technology solutions are mostly at the prototyping stage and have not reached commercialisations. Without adequate skills and capabilities, RAS solutions may not mature to meet the offshore wind sector's needs. The market size for RAS in offshore wind O&M services is forecasted to be around £341 million annually by 2030. The slow adoption of advanced robotic technology is primarily due to high costs and limited field-testing opportunities. To overcome these challenges, there is a need for more repeatable and accurate testing and validation, alongside the development of new workforce strategies to address skill gaps[185].

OREC's Operations and Maintenance Centre of Excellence (OMCE) is a national hub to enhance offshore wind's operational performance. OMCE works with UK industry to drive solution-focused innovation and improvements in O&M. There programmes include a 5G PORTAL tested which allows for testing and demonstration of robotics and autonomous systems within a full-scale operational wind farm. They also have a simulation tool - Synthetic Test and Unified Demonstrations System (STUDS) - where fleets of robotics and autonomous systems can be demonstrated in a virtual environment.

Additionally, there are several projects and start-ups developing robots for maintenance and repairs for wind farms. BladeBUG[186] is developing advanced robots to perform detailed remote contact inspections and early-stage repairs of wind turbine blades in a cheaper, safer and faster way than is currently done by technicians. These robots can be operated remotely and in both an onshore and offshore environment. BladeBUG's current prototype robot has deployed on a 7MW offshore turbine.

The project UNITE is developing AI and control systems to allow underwater robots to operate autonomously in turbulent seas. The technology is undergoing trials as part of UNITE (Underwater Intervention for Offshore Renewable Energies). The vision of the UNITE project is to develop a holistic solution to autonomous and semi-autonomous underwater intervention applied to the maintenance and repair of offshore wind farms, remotely monitored from shore and safely operated worldwide[187].

Solar	Production
	Electrical
Robotics and Autonomous Systems	4

Table 26 - Solar: Robotics and Autonomous Systems Score

Cybersecurity

The solar inverter converts DC power produced by solar panels into AC usable electricity and connects the panel to the grid. Cybersecurity is required to prevent hacking of the inverter, which could hinder energy production or endanger the power grid's stability.

The Network and Information Systems (NIS) Regulations 2018 applies to renewables that meet the supply thresholds. Smaller solar companies may not supply a large enough energy to consumers to be required to comply with these regulations. The UK Product Security and Telecommunications Infrastructure (PSTI) Regime came into force in April 2024 and mandates that all manufacturers of internet connected devices, including solar energy infrastructure, must meet basic cybersecurity standards.

Although critical national priority, solar farms are not yet classed as Critical National Infrastructure the implication is that cybersecurity will be of increasing importance but is not expected to be as highly adopted as other energy solutions.

Solar	Production
	Electrical
Cybersecurity	5

Table 27 - Solar: Cybersecurity Score

184 University of Strathclyde (2023), 'Digital twin' project will inform future innovation in the UK energy industry'
185 OREC (2024), 'Robotics and autonomous systems: increasing UK offshore wind capacity'
186 BladeBUG
187 One Network (2024), 'AI to enable autonomous underwater robots to maintain offshore wind farms'

Summary and Overall Scoring

In the figure below outlines the adoption of digital technology for electrical production only - in contrast to earlier energy types, solar energy cannot be produced, but would be stored or distributed via the electrical network (considered separately). Solar panels and farms do not require significant ongoing maintenance and operational control. By default, they can be managed remotely, with levels of predictive analytics and AI applied from the outset. Robotics are not readily deployed for all applications and digital twins, although models are used, do not seem to feature highly.

Solar	Production
	Electrical
Artificial Intelligence	6
Remote Operations	6
Digital Twins	4
Robotics and Autonomous Systems	4
Cybersecurity	5

Table 28 - Solar: Overall scoring

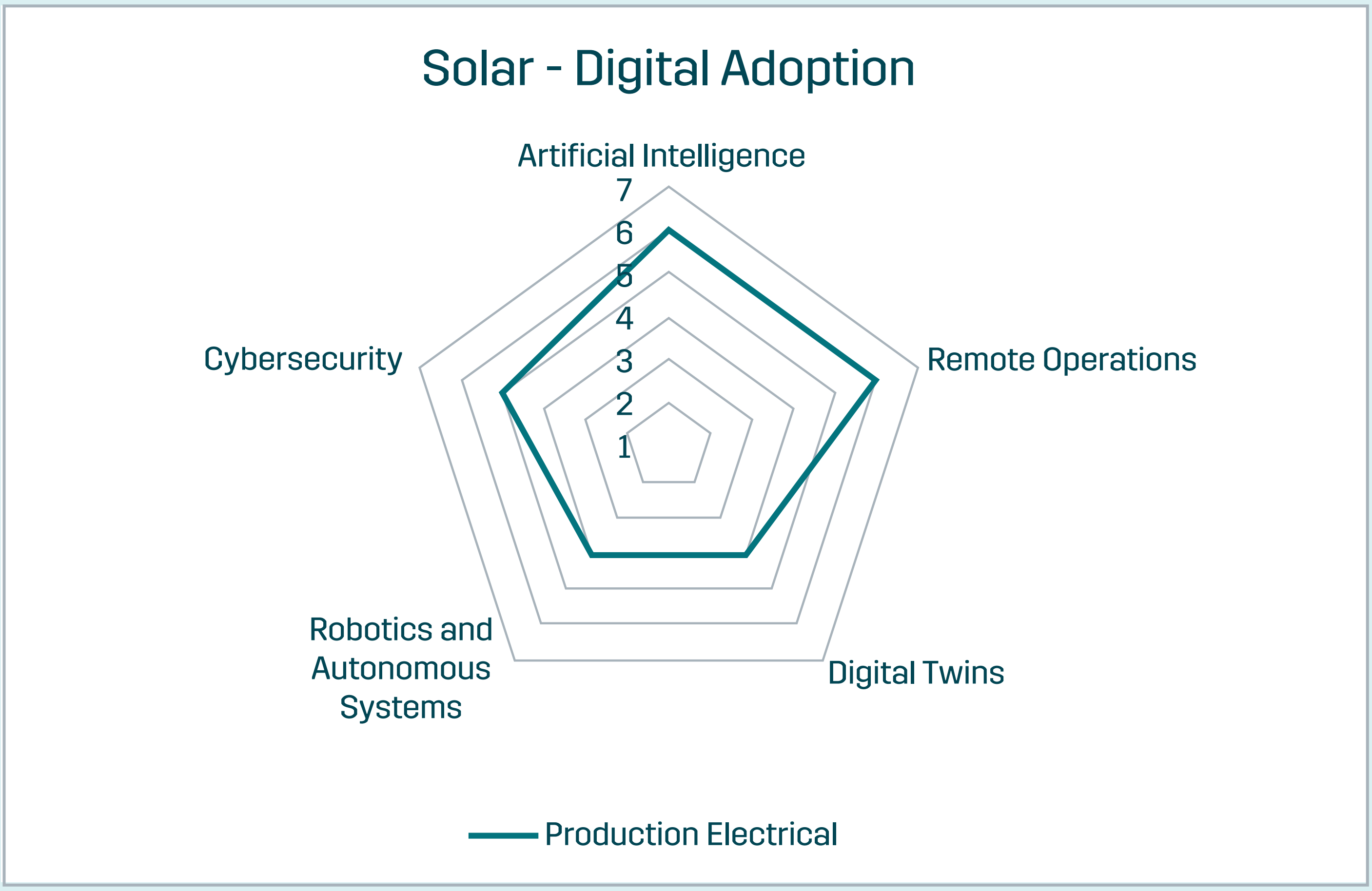

Figure 24 - Solar Scoring

37. Wind

A survey conducted by The Offshore Renewable Energy Catapult (OREC) in 2019 revealed that 94% of respondents perceived a gap between the current operational practices of the offshore wind industry and it's optimal functioning to maximise the potential of data and digital technologies[188].

Several digital technologies are currently available for wind farm developers. Drones are being used across the UK to aid in turbine inspection due to their ability to quickly generate high quality images and videos, and access difficult to reach areas. Sensors continuously monitor wind turbine blades remotely, essentially IoT devices often with edge computing incorporating AI/ML algorithms. Digital twin modelling tools are used to aid wind developers and to support operations and maintenance.

Research is looking to AI to improve efficiency by optimising the design of wind turbines and farms, helping to manage integration into the grid, and improve weather forecasts, to digital twins for monitoring and optimising offshore wind operations, and to robotics to improve efficiency and safety during O&M at offshore wind farms. Aside from drones used for inspections, current solutions are mostly at the prototype stage and have not reached commercialisation.

The Strategic Energy and Technology Plan (SET Plan)[189] community on wind energy agrees on a common European strategy for wind research and competitiveness by 2050. One of their five long-term targets by 2050 is to have harnessed the potential of digitalisation and automation with high cybersecurity standards[190]. A timeline for R&I in the wind sector can be found in the below.

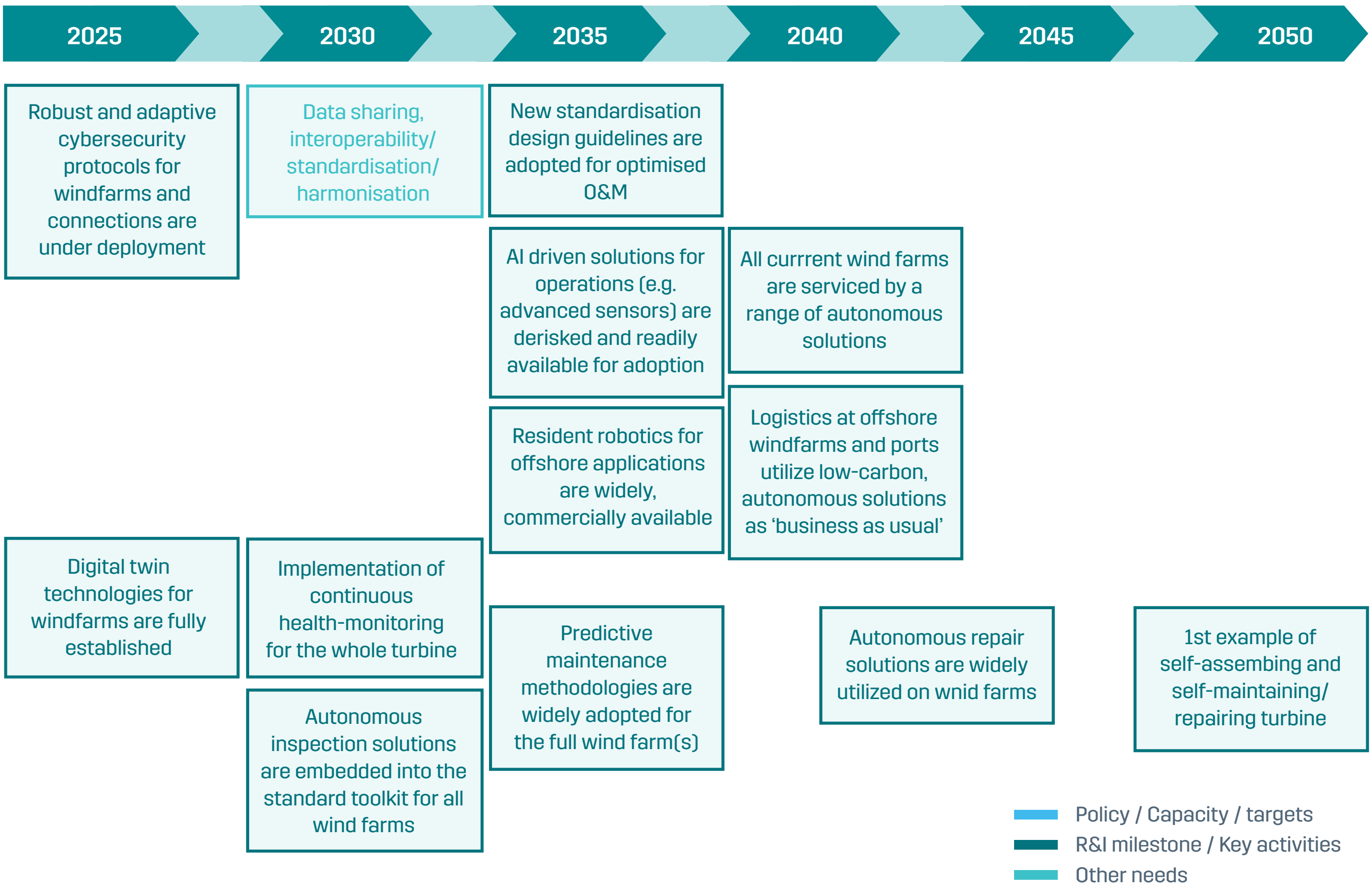

Figure 25 - Research and Innovation timeline for harnessing digitalisation for Wind[191]

[188] Offshore Renewable Energy Catapult (OREC) (2019), 'Survey identifies gap in adoption of data and digitalisation in the offshore wind sector'
[189] EU, 'Strategic Energy Technology Plan'
[190] European Technology & Innovation Platform on Wind Energy (ETIP Wind) (2025), 'From Innovation to Industrial Competitiveness'
[191] ETIP Wind (2025), 'From Innovation to Industrial Competitiveness'

Artificial Intelligence

AI enables adjustment to weather and wind conditions, improved planning and operational efficiency, and eliminates unnecessary shutdowns due to weather. Wind operators are also using AI for predictive maintenance and to monitor and optimise turbine performance.

Adoption of AI in the wind energy sector is progressing, but there is still a lot of research and innovation required.
OREC is engaging in several new programmes to understand how AI and digital technology can revolutionise how they consent, progress, manage and maintain the offshore wind sector. Their research team have developed AI to analyse live operational SCADA (supervisory control and data acquisition) data to predict faults on offshore wind turbine components several weeks before they occur[192].

A key application of AI is in the design phase to increase efficiency of wind farms. EvoPhase have developed the world's first urban wind turbine designed by AI and tailored to unique wind conditions for a specifical geographic area - the Birmingham Blade is up to seven times more efficient than existing designs[193]. The Alan Turing Institute carried out research using ML to increase accuracy of modelling wind farms to improve wind farm efficiency. Their next step is to improve the model's accuracy by incorporating weather data[194].

In the last year, several projects have received funding to advance the use of AI within the wind energy sector. Polaron - a spin out from ICL - speeds up the development of material used in windfarms from years to days and has won the government's £1 million Manchester Prize[195]. EDF Energy R&D UK has been awarded funding to use AI to optimise wind farm design to reduce space requirements for offshore windfarms without reducing energy output[196]. Additionally, the University of Nottingham received funding to improve weather forecasting to manage renewables for the electricity grid.

With some applications of AI appearing in both the design and operations/maintenance of wind turbines it is clear that there is a level of adoption, however, given the volume of research into better and alternative ways to optimise wind farms, improve performance and drive operational benefits, the industry message is that the current deployed technology is not yet at a level of maturity. The levels of adoption, on the other hand are believed to be reasonable and encouraging.

Wind	Production
	Electrical
Artificial Intelligence	5

Table 29 - Wind: Artificial Intelligence Score

Remote Operations

Remote technologies are vital for UK wind turbine management, enhancing efficiency, safety, and cost-effectiveness. Wind farms use advanced remote monitoring systems to oversee turbine performance, detect faults, and perform corrective actions without technicians on-site. These 24/7 systems provide real-time surveillance, data analysis, and operational reports.

Remote control centres troubleshoot, commission, and optimise turbines, reducing downtime and improving performance, especially for offshore assets where access is difficult and costly.

Digital twins and IoT sensors enable operators to monitor and control wind turbines remotely. This is crucial for offshore turbines in harsh environments. Drones and robotics are used for inspection and maintenance, with drones offering advantages offshore, despite logistics being simpler onshore.

Wind	Production
	Electrical
Remote Operations	7

Table 30 - Wind: Remote Operations Score

192 OREC (2024), 'Artificial Intelligence - Driving forward the future of offshore wind deployment'
193 University of Birmingham (2024), 'The Birmingham Blade: the world's first geographically tailored urban wind turbine designed by AI'
194 The Alan Turing Institute (2023), 'Using machine learning to design more efficient offshore wind farms'
195 DSIT (2025), 'British start-up wins £1 million AI prize for breakthrough slashing materials development from years to days'
196 DESNZ (2024), 'Government backing for AI businesses to deliver net zero with innovative technologies'

Digital Twins

Digital twins enable operators to test different scenarios and optimise turbine performance. AI-powered digital twins can be used to detect faults, such as wear on turbine blades or faulty components, and alert operators to act. This minimises downtime and ensures turbines operate at peak performance.

Several projects started in 2022 and 2023 to advance the use of digital twins for the wind sector:

- The TetraSpar wind demonstration project will develop a digital twin for real-time monitoring of floating wind turbines. This virtual replica will allow remote performance monitoring, early fault detection, and predictive maintenance for the foundation, tower, and mooring lines. Machine learning and finite element analysis models will create this digital twin with embedded pre-trained algorithms[197,198].
- OREC's DOME (Digital Offshore Wind Measurement and Evaluation) Project aimed to develop a virtual environment to improve planning and maintenance of offshore wind farms. DOME will provide offshore wind developers and operators a unique platform to progress, demonstrate and test solutions facing the industry within a virtual world[199].
- In 2022, SSE Renewables, Microsoft and Avande launched a project to develop Azure Digital Twins for offshore wind farms to monitor environmental impacts and optimise operations[200].

More recently, a £1.95m EPSRC Fellowship aims to enhance offshore wind structure design using geometric digital twins and computational structural engineering[201].

Prior to installation all wind farms will carry out some form of modelling and simulation. The wind sector relies on Computational Fluid Dynamics (CFD) modelling to predict power production and maintenance scheduling requirements for offshore and onshore wind farms and research is ongoing to improve models to increase reliability and understand turbine fatigue.

The SWEPT2 project[202] was a collaborative project between SSE, DNV-GL, The Centre for Modelling & Simulation, OREC and others, and developed a new CFD capability for wind turbine modelling. The capability is freely available for academic use and can be used commercially with a licence.

The MAXimising wind Farm Aerodynamic Resource via advanced Modelling (MAXFARM) project simulates real-world wind conditions and investigates their impact on turbines. The project investigated the impact of atmospheric boundary layer (ABL) on turbine blades and the implications of fatigue[203].

FutureOn provides digital twins services for wind developers by creating a digital representation of their wind farm from seabed to turbine, to mitigate project risks[204].

Vattenfall uses digital twins to gain information on its entire fleet of wind farms, whilst also giving information at wind farm and individual turbine level. Their digital twins are based on data from sensors installed on the physical wind turbines. The sensors provide data of the structural behaviour of the individual wind turbine and that data are merged with all Vattenfall's other available data, such as operational and environmental data, into one common digital twin solution[205]. Vattenfall has an installed capacity of 1.1GW in the UK.

It is evident that the widespread use of digital modelling tools, which form the basis of digital twins, is there. How closely integrated the digital models are with the real asset is unclear. Scoring reflects that.

Wind	Production
	Electrical
Digital Twins	5

Table 31 - Wind: Digital Twins Score

[197] 2H (2023), '2H Amongst Winners of TetraSpar Innovation Challenge'
[198] Acteon, 'Navigating the future: AI-enabled digital twins for Cost-effective offshore wind farms'
[199] OREC (2023), 'Plans for new digital testing environment could revolutionise offshore wind development'
[200] SSE (2022), 'SSE Renewables, Microsoft and Avanade launch groundbreaking project to understand the impact of wind farms on ecosystems'
[201] Imperial (2024), 'Transforming Wind Energy Infrastructure with Digital Twinning'
[202] CFMS (2024) 'Wind Farm Modelling with Advanced Computational Fluid Dynamics'
[203] UK Research and Innovation (UKRI) (2021), 'Improving offshore wind farms by modelling their flow fields'
[204] Futureon - "Powering the future of offshore wind, faster"
[205] Vattenfall (2024), 'Digital twins - a road to more profitable offshore wind'

Robotics and Autonomous Systems

Offshore wind will need to increase sevenfold, necessitating operations in deeper, more remote waters. Robotics and Autonomous Systems (RAS) are crucial for the future of O&M in offshore wind farms. RAS can lead to significant improvements in efficiency and safety by reducing the need for human intervention. Current technology solutions are mostly at the prototyping stage and have not reached commercialisations. Without adequate skills and capabilities, RAS solutions may not mature to meet the offshore wind sector's needs. The market size for RAS in offshore wind O&M services is forecasted to be around £341 million annually by 2030. The slow adoption of advanced robotic technology is primarily due to high costs and limited field-testing opportunities. To overcome these challenges, there is a need for more repeatable and accurate testing and validation, alongside the development of new workforce strategies to address skill gaps[206].

OREC's Operations and Maintenance Centre of Excellence (OMCE) is a national hub to enhance offshore wind's operational performance. OMCE works with UK industry to drive solution-focused innovation and improvements in O&M. There programmes include a 5G PORTAL tested which allows for testing and demonstration of robotics and autonomous systems within a full-scale operational wind farm. They also have a simulation tool - Synthetic Test and Unified Demonstrations System (STUDS) - where fleets of robotics and autonomous systems can be demonstrated in a virtual environment.

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The project UNITE is developing AI and control systems to allow underwater robots to operate autonomously in turbulent seas. The technology is undergoing trials as part of UNITE (Underwater Intervention for Offshore Renewable Energies). The vision of the UNITE project is to develop a holistic solution to autonomous and semi-autonomous underwater intervention applied to the maintenance and repair of offshore wind farms, remotely monitored from shore and safely operated worldwide[207].

Robot drones are currently being used to carry out inspections of wind turbines. See the remote operations section for more detail.

Drones are a valuable tool for inspecting wind turbines. They can carry out inspections over large areas quickly, generate high-resolution images and videos and access difficult-to-reach areas. Drones are being used across the wind industry. For example, Drone Site Surveys regularly carry out wind turbine surveys across the UK[208], and heliguy[209] provides drone consultancy, supply, support, training and reports for UK wind turbine inspections. Perceptual Robotics incorporates AI into their autonomous drones. The drones carry out inspections in minutes, providing the data to carry out predictive analysis and reduce costs[210].

Wind	Production
	Electrical
Robotics and Autonomous Systems	4

Table 32 - Wind: Robotics and Autonomous Systems Score

[206] OREC (2024), 'Robotics and autonomous systems: increasing UK offshore wind capacity'
[207] One Network (2024), 'AI to enable autonomous underwater robots to maintain offshore wind farms'
[208] Drone Site Surveys, 'Wind Turbine Inspection'
[209] Heliguy, 'Drones for wind turbine inspection'
[210] Perceptual Robotics, 'Drone Site Surveys, 'Wind Turbine Inspection'

Cybersecurity

There is a growing awareness of the need for robust cybersecurity measures in the wind industry in both the UK and wider Europe. RenewableUK recently held its first seminar on cybersecurity and improving cybersecurity and resilience of the energy system is considered a main element of the SET Plan strategy[211].

Analysis by The Alan Turing institute shows that offshore wind needs urgent protection from cyberattacks. Due to their remote location, they require more digital infrastructure to communicate with onshore systems. Many wind farms also rely on older software and communication systems that were not designed with cybersecurity in mind. Integrating modern digital solutions with old infrastructure can increase the susceptibility to cyberattacks[212].

Current regulation includes the Network and Information Systems (NIS) Regulations 2018. NIS provides legal measures to boost the overall level of security (both physical and cyber) of network and information systems critical for essential services[213]. Some wind turbines may not generate enough energy to need to comply with these regulations.

Given the ongoing need for increased cybersecurity, the scoring reflects the levels of adoption (high), but it is noted that the technology deployed will need a continual refresh to maintain a level of maturity and resilience.

Wind	Production
	Electrical
Cybersecurity	6

Table 33 - Wind: Cybersecurity Score

[211] European Technology & Innovation Platform on Wind Energy (ETIP Wind) (2025), 'From Innovation to Industrial Competitiveness'
[212] Centre for Emerging Technology and Security (CETaS), 'Enhancing the Cyber Resilience of Offshore Wind'
[213] The NIS Regulations 2018

Summary and Overall Scoring

Like Solar, Wind only considers the production of electricity, i.e. power. There is a similar spread of adoption levels however higher expected use of digital twins and robotics with AI slightly lower as predictive capability do not appear to be applied uniformly for wind turbine operation.

Wind	Production
	Electrical
Artificial Intelligence	5
Remote Operations	7
Digital Twins	5
Robotics and Autonomous Systems	4
Cybersecurity	6

Table 34 - Wind: Overall scoring

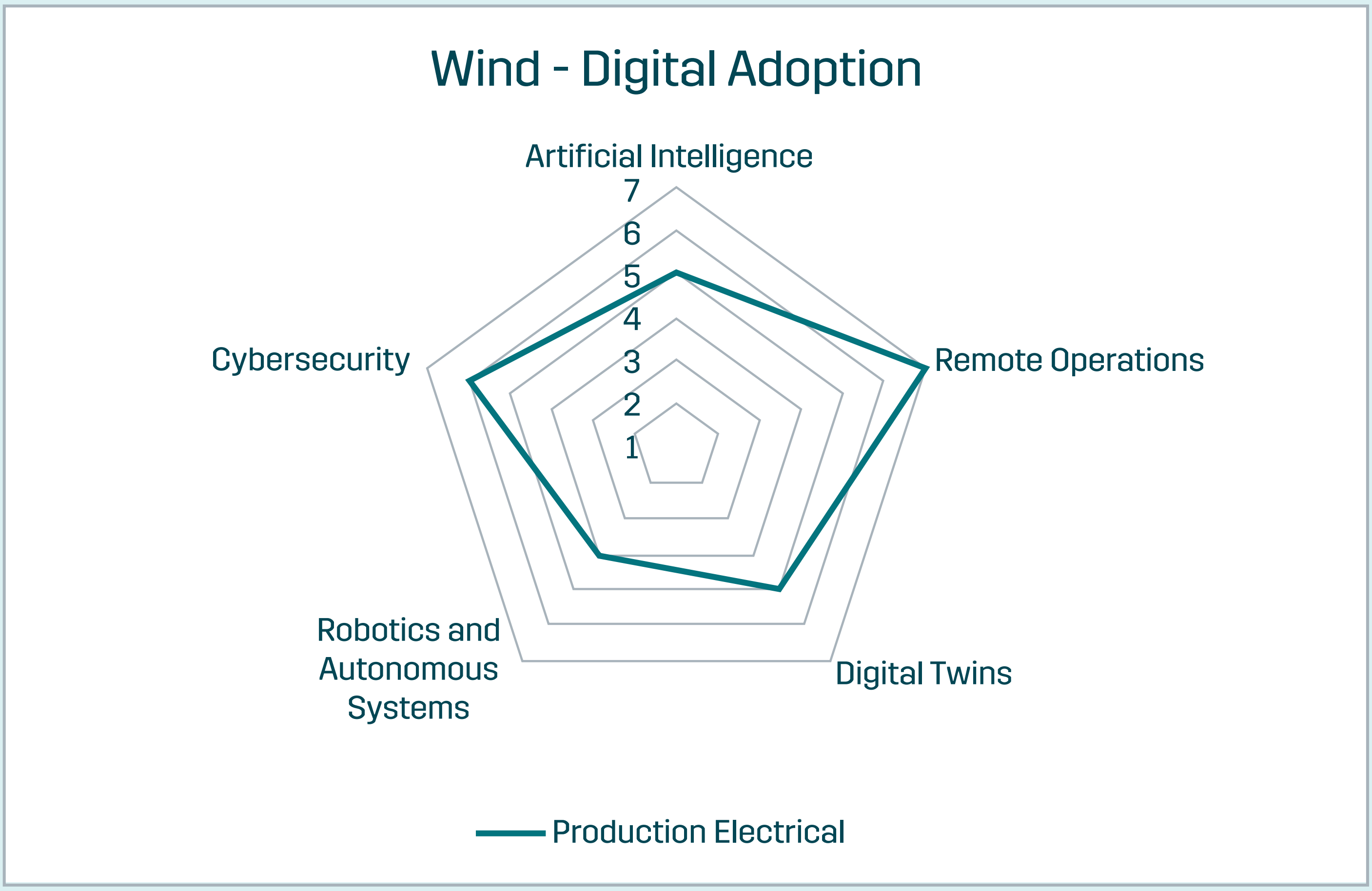


Figure 26 - Wind Scoring

38. Geothermal

Geothermal energy can be used for heating, or to generate electricity. Excess heat can be stored for a longer duration than other energy storage technologies. Currently there are limited large scale geothermal projects in the UK[214]. In 2023, the Eden geothermal project in Cornwall became the first operational deep geothermal project in the UK since 1986[215]. As of 2023 there were 11 aquifer thermal energy storage developments with 9 in London and most <1MW_{th}.

Due to the immature nature of geothermal within the UK, there is limited adoption of digital technologies. The world's first AI heat pump was installed in November 2024[216], which may pave the way for AI to be integrated into ground sourced heat pumps. For deep geothermal, simulation and modelling are important to identify the best resource and identify the best geothermal technology for the application.

Deep geothermal has the potential to take advantage of the learnings from the oil and gas activity. Recently there has been increased interest from oil and gas companies into geothermal, which may help speed up both the number of geothermal projects in the UK and the adoption of digital technologies into the sector. Research and analysis by the Government Office for Science on the "Future of the subsurface: geothermal energy generation in the UK" highlighted the need for more accessible digital data interoperable across all geological types.

In summary, geothermal energy in the UK is underdeveloped, with limited projects and digital adoption is minimal as a result.

Artificial Intelligence

There is limited adoption of artificial intelligence within geothermal applications within the UK, with the most notable geothermal projects not mentioning its use. However, a lot of the learnings from the oil and gas industry can be applied to deep geothermal operations and increased interest in geothermal by oil and gas companies may advance adoption. AI can be used in drilling, reservoir characterisation, risk management operational optimisation. Geothermally active regions like China and Iceland, uses AI models for a range of applications including estimating drilling times to forecasting geothermal properties[217].

As there are few commercial geothermal projects in the UK, AI for geothermal isn't yet a main area of research. However, in 2023, Imperial College London launched the "Smart assessment, management and optimisation of urban geothermal resources (SmartRES). SMARTRES is a broad, multidisciplinary project that brings together research on the geoscience and geoengineering of shallow geothermal technology, use of AI to manage and optimise urban geothermal deployments, and responsible innovation including societal engagement[218].

For all areas of heat management from production to storage and transport, the adoption of AI is regarded as in its initial stages. With much to be learned from other sectors, the UK does not yet have sufficient geothermal facilities in place.

Geothermal	Production	Storage	Transport
	Fuel (Heat)	Fuel (Heat)	Fuel (Heat)
Artificial Intelligence	3	2	1

Table 35 - Geothermal: Artificial Intelligence Score

214 IEA Geothermal (2024),'2023 United Kingdom Country Report'
215 EdenGeothermal, 'Geothermal Energy: as secure as the ground beneath your feet'
216 EcoExperts (2024),'Wondrwall unveils first AI heat pump'
217 Al-Fakih et al (2023), 'Application of machine learning and deep learning in geothermal resource development: Trends and perspectives'
218 Imperial Collage, 'SMARTRES'

Remote Operations

Geothermal operations require remote monitoring and control of facilities such as steam and reinjection wells which can be located at a considerable distance from a geothermal plant. Although it is a low margin industry in the UK the use of digital solutions is expected to provide efficiencies and performance improvement, however investment is not yet sufficient to support test/trial/implementation.

It is likely that existing heat networks are managed remotely compared to production. With the increasing application of Distributed Temperature Sensing (DTS) and Distributed Acoustic Sensing (DAS)downhole to monitor performance then it is also expected that remote operations for production would increase.

Yokogawa provides monitoring and control solutions for geothermal in the UK. Their solutions include their Plant Resource Manager (PRM) - an integrated device management software package that enhances maintenance efficiency by making it possible to remotely monitor the status of devices and make changes to their settings[219]. Noise from geothermal sites must be kept within set limits. The United Downs deep geothermal project in Cornwall utilises sound level monitors (SLMs) to measure noise[220].

Globally, many geothermal plants are being operated remotely. For example, Mitsubishi Hitachi Power Systems has established a Remote Monitoring Centre which supports O&M for various power generating equipment including geothermal power systems.

Geothermal	Production	Storage	Transport
	Fuel (Heat)	Fuel (Heat)	Fuel (Heat)
Remote operations	2	3	3

Table 36 - Geothermal: Remote Operations Score

Digital Twins

In the UK, there are initiatives and interest in digital twins for energy infrastructure, which would include geothermal. However, no mention of digital twins specifically for geothermal was found.

Modelling and simulation are used to quantifying the geothermal resource available, with modelling tools in the UK available for over 10 years[221]. Oil and gas operators are starting to consider geothermal as a potential area for future investment and would therefore be able to apply their extensive knowledge and modelling and simulation tools to geothermal applications. However, the lack of subsurface data is a barrier to geothermal development.

Imperial College London (ICL) is using the Imperial College Finite Element Reservoir Simulator (IC-FERS) to simulate multiphase flow and transport in geothermal reservoirs. They are collaborating with other industry and academic groups worldwide who are researching and implementing new methods for drilling and operating geothermal wells[222].

Outside of the UK, the Netherlands is key player in the development and deployment of digital twin technology for geothermal, with several initiatives. Project GEMINI in the Netherlands uses digital twins to help operators monitor, forecast and manage the highly complex systems in geothermal plants to optimise the geothermal system performance[223]. New Zealand and Turkey are also looking into the deployment of digital twins for geothermal.

Geothermal	Production	Storage	Transport
	Fuel (Heat)	Fuel (Heat)	Fuel (Heat)
Digital Twins	3	2	1

Table 37 - Geothermal: Digital Twins Score

[219] Yokogawa - Geothermal Power - Plant Resource Manager (PRM)
[220] GEL energy - United Downs deep geothermal project - sound level monitors (SLMs)
[221] Scottish Enterprise, 'Geothermal Market Opportunity Profile - Modelling and Simulation'
[222] Imperial College London (ICL) - 'Geothermal Energy'
[223] TNO (2023), 'Gemini: intelligent decision support system for geothermal assets'

Robotics and Autonomous Systems

There was no information found on current use of robotics in the UK for geothermal. However, globally robots are being used to drill to access geothermal heat at depths a long way below the surface. For instance, a Swiss company called Borobotics have unveiled a prototype autonomous drill for geothermal applications which is seeking to make harnessing geothermal energy less expensive and more accessible. The robot has sensors which allow it to detect the type of material is boring through[224].

Geothermal	Production	Storage	Transport
	Fuel (Heat)	Fuel (Heat)	Fuel (Heat)
Robotics and Autonomous Systems	1	1	1

Table 38 - Geothermal: Robotics and Autonomous Systems Score

Cybersecurity

Reservoir data system monitoring for geothermal is a vulnerable to cyber-attacks. As geothermal resources increase, cybersecurity will become increasingly important. Although different to oil and gas, the operations are similar in nature and geothermal has an opportunity to build on best practice from the oil and gas industry. No specific mention of cybersecurity within geothermal was found within the UK and although geothermal energy isn't an energy source, it isn't explicitly included within NIS regulations.

Geothermal	Production	Storage	Transport
	Fuel (Heat)	Fuel (Heat)	Fuel (Heat)
Cybersecurity	3	3	2

Table 39 - Geothermal: Cybersecurity Score

[224] CleanTechnia (2025), Borobotics

Summary and Overall Scoring

From Section 38, and considering the low levels of geothermal asset deployment within the UK, it is little surprise that adoption levels are also low. This marks a significant opportunity to design-for-digital and avoid retrofitting digital technology once the asset(s) are in operation.

Geothermal	Production	Storage	Transport
	Fuel (Heat)	Fuel (Heat)	Fuel (Heat)
Artificial Intelligence	3	2	1
Remote Operations	2	3	3
Digital Twins	3	2	1
Robotics and Autonomous Systems	1	1	1
Cybersecurity	3	3	2

Table 40 - Geothermal: Overall scoring

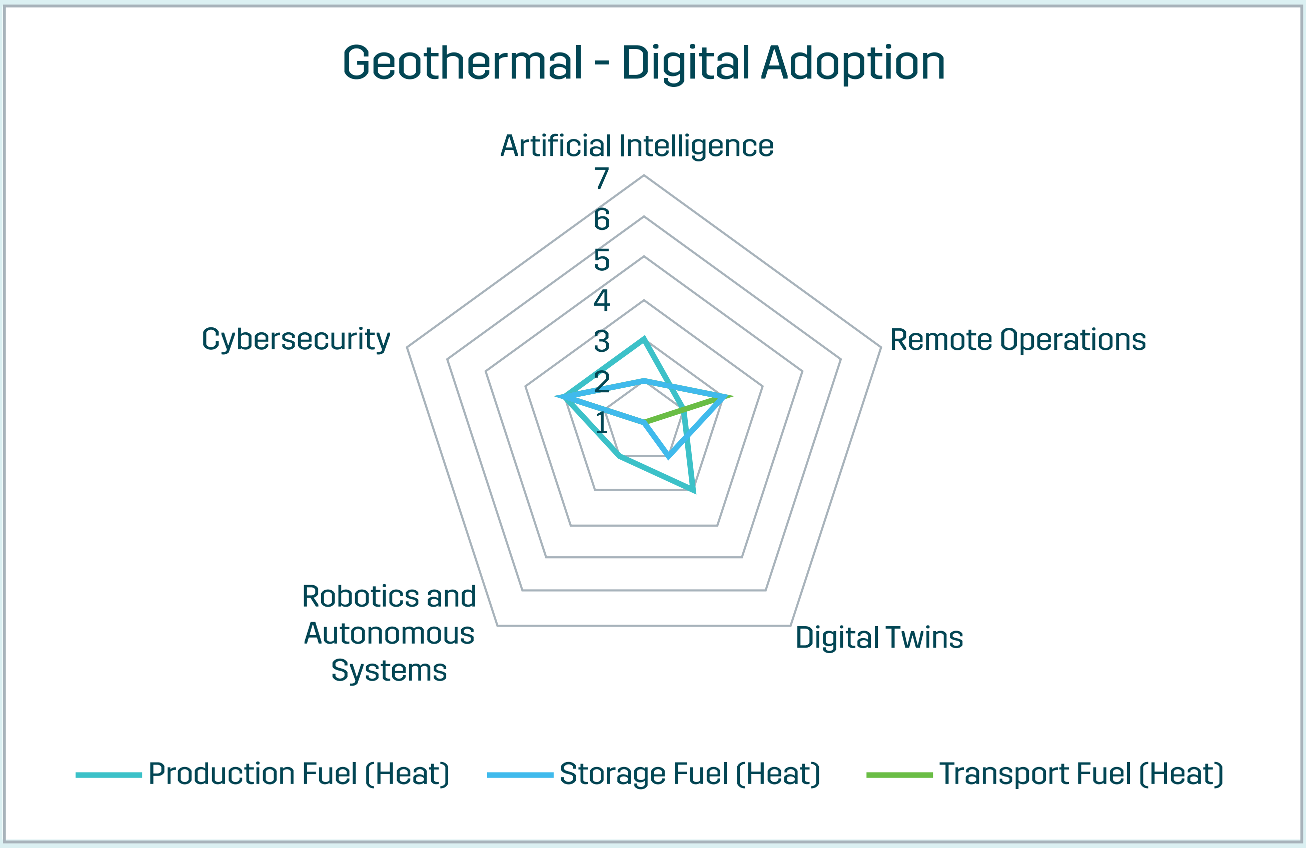


Figure 27 - Geothermal Scoring

39. Wave, Tidal and Hydro

Wave, tidal and hydropower appears to have a low level of digital adoption currently. Despite the UK having generated electricity from hydropower since 1878, there are far fewer new projects than other technologies such as wind and solar, and less focus on incorporating digital technologies into operation. Wave and tidal projects on the other hand are emerging technologies and it is expected that AI will become integral to operations of these energy projects. Currently there is limited evidence due to the small-scale deployment.

Digital technologies for wave, tidal and hydropower are mostly at demonstration stage or earlier, but simulation and modelling and remote operations are further ahead. For example, there are several tools available to model tidal activity in UK waters. Remote operations are also being used to some extent to enable onshore visibility of offshore operations and research is ongoing to incorporate AI to enhance energy generation. Development is required for robotics that can have stable operation in turbulent seas to deliver tidal turbine maintenance[225].

Artificial Intelligence

The ELEMENT (Effective Lifetime Extension in the Marine Environment for Tidal Energy) project was a four year EUR5mn Horizon 2020 project which created an intelligent control system within a tidal energy turbine. The project, a collaboration between 11 partners including tidal energy developer Nova Innovation and ORE Catapult, included a test in France which resulted in 17.7% cost reduction through gains in yield, reduction in damage and turbine lifetime extension. The final project phase involved installing the system in an offshore environment in the Shetland Tidal Array in Scotland[226].

Elsewhere in the world, Swedish wave energy developer CorPower Ocean secured funding from Sweden's national innovation agency, Vinnova, to integrate AI into its wave energy technology in collaboration with the Norwegian University of Science and Technology. The WACE (Wave energy AI-based Control Enhancement) project, running until November 2025, aims to optimise performance and control strategies for wave energy converters (WECs). CorPower Ocean's WECs incorporate a tuning and detuning mechanism that adjusts to ocean conditions, limiting response in storms while amplifying power capture in regular waves. The WECs generate vast amounts of data, and the project will leverage this data to refine model-predictive control strategies, combining AI with existing optimal control methods to enhance operational efficiency while maintaining system stability[227].

Wave/Tidal/Hydro	Production
	Electrical
Artificial Intelligence	4

Table 41 - Wave/Tidal/Hydro: Artificial Intelligence Score

[225] OREC (2024), 'Tidal Stream Technology Roadmap'
[226] OREC (2023), 'New intelligent turbine project demonstrates the cost of tidal energy could be reduced by 17 per cent'
[227] CorPower Ocean (2025), 'CorPower Ocean and NTNU partner on AI-based wave energy project'

Remote Operations

Remote operations play a critical role in enhancing the efficiency, reliability, and cost-effectiveness of wave and tidal energy systems in the UK. These technologies address challenges such as harsh marine environments, maintenance costs, and grid integration.

Tidal turbines use accelerometers and acoustic emission sensors to monitor vibrations across low- and high-frequency regimes. This enables early fault detection in components like gearboxes, reducing unplanned downtime.

Brunel University's REMO (Online remote condition monitoring of tidal stream generators) aimed to create a novel condition monitoring (CM) system to reduce projected lifecycle and maintenance costs of tidal-stream energy by 50% and the generator downtime to a level comparable with wind turbines. The key objective of the project was to create a system capable of remotely and permanently monitoring the entire frequency spectrum of structural vibrations generated by all the rotating components of a tidal stream turbine. The developed prototype, now at the demonstration stage, assesses the structural and mechanical integrity of tidal systems to provide advanced warning of the presence of faults and impending failures[228].

By default, as all wave and tidal resources are autonomous, remote operations is needed if only to monitor the operation.

Wave/Tidal/Hydro	Production
	Electrical
Remote Operations	5

Table 42 - Wave/Tidal/Hydro: Remote Operations Score

[228] Brunel University (2023), 'Online remote condition monitoring of tidal stream generators'

Digital Twins

Tidal and wave energy systems in the UK are increasingly leveraging digital twin technology to optimise performance, reduce costs, and accelerate the transition to net zero. Some key applications are for

- site assessment and resource modelling: mapping tidal currents and wave patterns combining 2D and 3D modelling methods to enable turbine placement
- tidal stream energy forecasting: combining satellite and metocean digital twins to predict tidal current velocity and energy output, critical for feasibility studies and securing investments
- performance improvement: dynamic adjustment to resources can be made by utilising digital twins to adjust operational parameters in response to sea conditions.
- structural health monitoring: sensors on energy assets can be fed into digital twins to determine mechanical stress or corrosion.

Simulation and modelling of tidal and wave is being used by developers to help predict energy generated at sites.

In 2012, the Energy Technologies Institute completed a project to assess the tidal energy potential around the UK, helping to inform turbine design, assess interactions of tidal range and tidal current systems across the UKCS, and evaluate their impact on European coasts. Now complete, the project has been launched to market under the brand of SMARTtide which is available to the marine industry under licence from HR Wallingford.[229].

NOC have developed Polpred to help organisations in the marine renewable energy sector visualise and predict offshore tides and water elevation in a particular area[230].

Additionally, Tidetech provides tidal model output as forecast or hindcast and tide surge models. The models have been used to provide the UK Storm Surge Forecasting Service and are used in many tidal power projects[131].

Within the research community, the EU-funded Iliad Project comprising 56 international partners (including the UK) uses digital twins to provide accurate predictions of sea behaviour and ensure a healthy sea economy. The project included a practical study of the Inner Sound of the Pentland Firth, UK[232].

The Energy System Digital Twin project mentioned in the solar digital twin section 36 includes the integration of tidal.

Elsewhere, in the US, digital twins are being used to simulate different scenarios, like low water flow or varying water levels. The Digital Twins for Hydropower Systems platform was launched in 2023 and has seen significant enhancements with updates in 2024. The framework is a collaboration between the Department of Energy's Pacific Northwest National Laboratory (PNNL) and Oak Ridge National Laboratory (ORNL). The platform allows dam operators to monitor, simulate, and optimise their machinery, reducing unexpected outages and extending the lifespan of aging infrastructure. The digital twin can record and simulate changes made to the dam over subsequent years, which is meant to help pass down knowledge and help future generations make decisions[233].

Wave/Tidal/Hydro	Production
	Electrical
Digital Twins	4

Table 43 - Wave/Tidal/Hydro: Digital Twins Score

[229] UKERC (2012), 'Tidal Modelling - Interactions: Analysis and Conclusions Report'
[230] National Oceanography Centre, 'Marine Renewable Energy'
[231] Tidetech, 'Our tide and tide surge models'
[232] Iliad (2022), 'Study on Tidal Array Spatial Optimisation Presented by Iliad at IAHR Congress'
[233] Sean Wolfe (2024), 'Digital twins: modernizing the oldest source of clean energy'

Robotics and Autonomous Systems

There is widespread use and acceptance of robotic and autonomous systems in the marine environment, particularly in the oil and gas industry. The technology and lessons from the oil and gas industry can be used to develop robots for marine technology such as tidal or wave.

Robotics adoption in the UK's wave, tidal, and hydro sectors is accelerating innovation, safety, and cost-efficiency. With significant transferability from oil and gas and offshore wind, the adoption rate is expected to grow considerably.

Organisations such as Orbital Marine Power, HydroWing and ACUA Ocean are deploying robotics systems to provide inspection, maintenance and monitoring of tidal turbines.

The National Oceanography Centre (NOC) has unveiled a new Innovation Hub in Southampton to advance ocean technology. The facility will advance innovation in marine autonomous systems (MAS). The hub replaces and expands on the former Marine Robotics Innovation Centre under NOC innovations[234]. In addition, the University of Edinburgh has developed new technology that enables robots to work stably in turbulent seas, making it cheaper and faster to maintain tidal turbines or offshore wind farms[235].

Wave/Tidal/Hydro	Production
	Electrical
Robotics and Autonomous Systems	3

Table 44 - Wave/Tidal/Hydro: Robotics and Autonomous Systems Score

Cybersecurity

The Network and Information Systems (NIS) Regulations 2018 applies to renewables including wave, tidal and hydropower. NIS provides legal measures to boost the overall level of security (both physical and cyber) of network and information systems critical for essential services[236]. Some marine companies may not supply a large enough energy to need to comply with these regulations.

From the research performed adoption is understood to be high, although variable. With tidal and wave energy still relatively immature, it is expected that cybersecurity requirements will be satisfied but may not be as mature as other sectors.

Wave/Tidal/Hydro	Production
	Electrical
Cybersecurity	5

Table 45 - Wave/Tidal/Hydro: Cybersecurity Score

234 National Oceanography Centre (2025), 'NOC launches new Innovation Hub to power ocean tech and blue economy'
235 University of Edinburgh (2024), 'Wave-predicting robots could cut green energy costs'
236 Department for Digital, Culture, Media & Sport (2018), 'The NIS Regulations 2018'

Summary and Overall Scoring

Wave, Tidal and Hydro Power have collectively been analysed and whilst a generalisation, there is equally a low level of digital adoption. This is expected due to low commercial activity, pressing financial models that leave digital technologies as a retrofit solution. Applications of AI and Robotics were regarded as opportunities for improvement. Digital twins, remote operations and cybersecurity were quite well established.

Wind	Production
	Electrical
Artificial Intelligence	4
Remote Operations	5
Digital Twins	4
Robotics and Autonomous Systems	3
Cybersecurity	5

Table 46 - Wave/Tidal/Hydro: Overall scoring

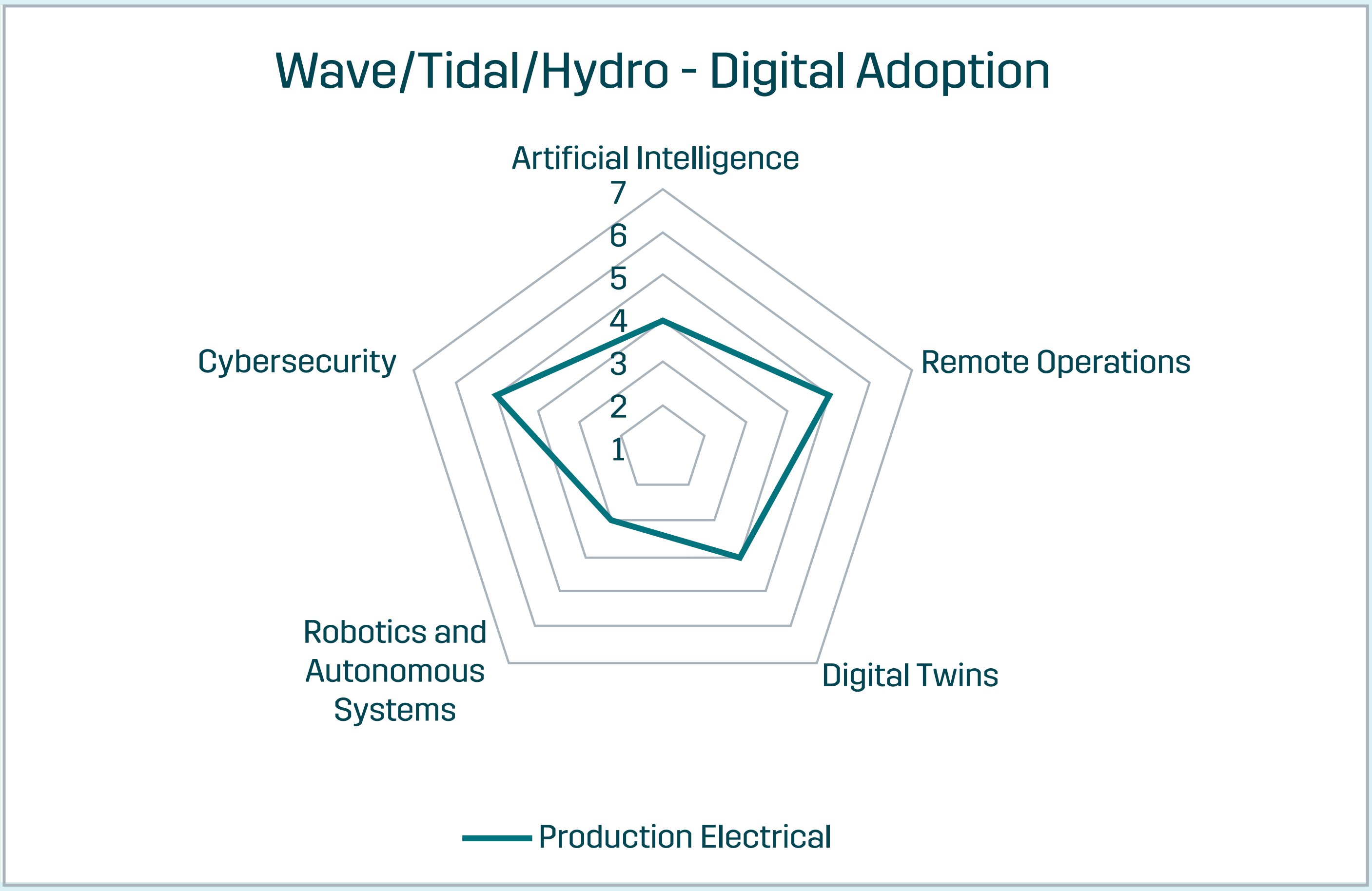


Figure 28 - Wave, Tidal, Hydro Scoring

40. CCUS

Digital technologies are important for CO_2 storage. Seismic interpretation and rock physics are required prior to injection of CO_2 to find suitable CO_2 reservoirs and predict how the CO_2 will react following injection. This is important to mitigate the risk of leakage and overpressure in the subsurface, as well as to predict how much CO_2 can be stored. Although CO_2 storage is still in its infancy in the UK, a lot of the learnings from oil and gas around the use of digital technologies can be applied to carbon storage for CCUS.

In the UK, the first injection of CO_2 occurred in 2025 in the Poseidon project with several other projects in the pipeline[237]. The Poseidon project carried out Monitoring Measurement and Verification (MMV) to determine if the CO_2 was behaving as predicted. Injection performance and multiphase flow stability exceeded model forecasts.

Researchers are looking at digital technologies to improve leak detection and CO_2 flow migration. For example, Heriot Watt is researching AI to reduce the time taken to model CO_2 flow migration whereas the Energy Technologies Institute (ETI) funded a three-year research programme back in 2014 that increased capability for marine robotics for leak detection.

More research is also needed on the adoption of digital technologies for capture, transportation and utilisation. As the industry is still developing, digital technology adoption is not a priority. At this stage, given utilisation of capture carbon is low within the UK, it will not be included in the analysis.

Artificial Intelligence

AI can enhance carbon capture, but the evidence found was at pilot/research stage.

By leveraging ML algorithms, AI can increase efficiency of the carbon capture process by adjusting operational parameters in real-time reducing costs. By using AI, companies ensure the materials and energy used are exactly what's needed, reducing waste, carbon footprints and operating costs. Using data from sensors AI can carry out predictive maintenance to reduce unnecessary downtime.

Capture

Evidence has been largely from academic organisations.

- University of Surrey: using AI can help capture 16.7% more CO_2 from a coal-fired power station using 36.3% less energy from the grid[238].
- Imperial College London is using AI and ML at their carbon capture pilot plant. Alongside ABB, they have developed an AI tool (My Measurement Assistant) to help troubleshoot problems. Students learn how to use AI for process maintenance at their carbon capture pilot plant and can use the AI tool to assist in a wide range of queries. The plant gives students experience in maintaining and operating the plant whilst also providing the skills needed to incorporate AI. The students learn how to use AI for process maintenance, as well as AI assisting with a wide range of queries[239].

Another area of development is that of AI-designed materials. A Cambridge and Amsterdam-based company CupsAI offers AI-designed materials for carbon capture. Their platform functions like a search engine for materials, allowing users to request specific properties for new materials on demand. The company has secured $30 million from European and US venture funds[240].

In summary, whilst there is activity, adoption remains low as these are primarily pilot projects.

CCUS	Production	Storage	Transport
	Fuel	Fuel	Fuel
Artificial Intelligence	2	3	2

Table 47 - CCUS: Artificial Intelligence Score

[237] Perenco-CCS, 'The Poseidon Project'
[238] University of Surrey (2024), 'AI could help power plants capture carbon using 36% less energy from the grid'
[239] Majid (2025), 'Bringing AI to carbon capture: how Imperial College is revolutionising plant operations'
[240] CupsAI (2024), 'CuspAI Secures $30M to Combat Climate Change with AI-Designed Materials'

Storage

AI can be used to analyse seismic data and rock properties to identify the best sites for CO_2 storage and be used to simulate the behaviour of CO_2 in geological formations over long periods. This can help predict CO_2 migration or leakage[241]. Researchers at Heriot Watt University have leveraged AI via the ECO-AI[242] project, funded by UKRI, for modelling CCS methods from 100 days down to 24 hours using advanced AI simulators.

The UK government also supports the use of AI and digital technologies in monitoring and regulating geological storage, ensuring that stored CO_2 is tracked and remains secure over time[243].

Transport

AI is currently being used in the UK to enhance the safety, efficiency, and environmental performance of carbon dioxide (CO_2) transportation through pipelines. The main applications include pipeline monitoring and leak detection, plus also used to optimise operations. For example, Drax Group[244], Klarian's partnership with British Pipeline Agency (BPA) for CO_2 pipeline operations and route selection[245].

AI is integral to the UK's carbon transportation infrastructure, focusing on real-time monitoring, predictive maintenance, leak detection, and operational optimisation to ensure safe and efficient transport from capture sites to storage locations.

Remote Operations

Only 20% of global sequestration sites are monitored by remote sensing methods[246] due to equipment specifications not yet meeting the requirements for small scale CO_2 leakage monitoring and high costs of acquiring quality data from expensive sensors. The main focus is on the remote monitoring of data, condition of the asset and leak detection/response.

Capture

Carbon capture plants are low in maturity and therefore any remote operations technology deployed will likely be IoT sensors to assess asset condition. Little evidence was found from the research performed. However, outside of the UK, ABB's distributed control system (DCS) ABB Ability™ System 800xA is planned to be used for the Northern Lights project to optimise efficiency and enable remote operation of the carbon capture terminal[247].

Storage

Remote operations technologies are currently being deployed within UK CCUS plants-particularly in offshore storage and monitoring-to ensure safety, efficiency, and regulatory compliance. Technology is deployed to provide early warning of leaks and storage integrity, so primarily from a monitoring, measurement and validation perspective rather than remote and autonomous operation.

CCUS	Capture	Storage	Transport
	Fuel	Fuel	Fuel
Remote Operations	2	3	2

Table 48 - CCUS: Remote Operations Score

[241] AI Competence (2024), 'Can AI Optimise Carbon Capture and Storage Efficiency'
[242] Heriot Watt University (2024), 'AI breakthrough accelerates carbon capture and storage from 100 days to just 24 hours'
[243] UK Gov (2025), 'UK Carbon Capture, Usage and Storage (CCUS)'
[244] Energy Tech Summit (2024), 'From capture to storage: AI transforming the carbon cycle'
[245] Klarian (2022), 'BPA Pump Optimisation'
[246] NZTC (2024),'Advanced Remote Operations (ARO) Full Landscape Study'
[247] ABB - ABB technology to be used in world's first open CO2 transport and storage infrastructure

Transport

Remote operations for transportation are primarily focussed on monitoring of process conditions with some remote adjustment of pipeline conditions. Modern pipeline management platforms aggregate data from distributed sensors along the transport route. These platforms offer remote dashboards and alarm systems, enabling engineers and operators to monitor pipeline integrity, receive instant alerts, and make informed decisions from offsite control centres.

Operators of UK CO_2 pipelines are deploying remote operations systems such as Real-Time Transient Models (RTTM)[248]. These systems continuously monitor pipeline conditions-pressure, flow, and temperature-from centralised control rooms. RTTM technology provides early detection and precise location of leaks or operational anomalies, allowing operators to respond rapidly without needing to dispatch field personnel. This enhances both safety and environmental protection during CO_2 transport.

Digital Twins

Digital twins together with computer modelling are being applied within the CCUS space, to model processes, simulate potential scenarios and aid in the design and operation of proposed systems. NVIDIA has reported the potential gains in modelling these complex processes[249] with overseas potential in the Dutch North Sea evidenced by Neptune Energy[250].

As a global solution, ABB is collaborating with Canadian simulation software provider Computer Modelling Group (CMG) to provide an end-to-end solution for CCS. ABB integrates its Ability OPTIMAX energy management system with above-ground digital twin technology and CMG's subsurface modelling. Additionally, the ABB CCS 360 digital twin solution can track the complex lifecycle for capture, transportation and storage[251].

Capture

The Environmental Agency has a project aimed to create and test a digital representation of the Humber industrial cluster within its environmental setting and identify environmental and operational limits by simulating the operation of multiple low carbon technologies, including carbon capture, now and in the future[252].

Storage

There is no clear no mention of digital twins being used in the Poseidon project; however, it is expected that some form of digital modelling will be used, just not widespread adoption. The CO2Stored database is a national repository modelling over 500 potential UK offshore storage sites, evaluating security, capacity, and injectivity for sites like the Northern North Sea aquifers, ensuring compliance with UK Net Zero targets.[253]

Transport

Digital twins are used more in transportation and storage than in capture at the. Pipeline systems are modelled and subsurface have been using digital twins in terms of static and dynamic reservoir models for decades.

CCUS	Capture	Storage	Transport
	Fuel	Fuel	Fuel
Digital Twins	2	3	3

Table 49 - CCUS: Digital Twins Score

[248] DNV, 'Real-Time Transient Model (RTTM) based leak detection for CO2 pipelines'
[249] NVIDIA (2023), 'Using Carbon Capture and Storage Digital Twins for Net Zero Strategies'
[250] Neptune Energy (2022),'Neptune Energy to use digital twins for Carbon Capture'
[251] ABB, 'Driving carbon capture and storage'
[252] Environment Agency (2023), 'Digital twin of an industrial cluster: a proof of concept on the Humber Estuary'
[253] UK Gov (2023), 'Deep Geological Storage of CO2 on the UK Continental Shelf'

Robotics and Autonomous Systems

Given the maturity and extent of CCUS development within the UK, the general levels of adoption are considered low at this stage, however the potential is clearly high as experience and knowledge would be leveraged from existing oil and gas experience. On this basis, the scoring is low across capture, storage and transport.

One example showed that The Energy Technologies Institute (ETI) funded a three-year research programme in 2014 that increased capability for marine robotics for carbon storage. It also the identified the need for low-power and hence long-endurance autonomous underwater vehicles for cost-effective wide-coverage surveys during baseline and repeat environmental surveys[254].

The National Oceanography Centre (NOC) Autosub Long Range (ALR) was deployed and a small CO_2 leak turned 'on'. The ALR then performed wide-area and fine-area searches over five days. The sensor on the vehicle processed in real-time a complex set of Solstice sonar, physical and chemical sensor data into useful information and identified leaks and regions of interest. The ALR was remotely controlled from shore. This allows a small local deployment team for CCS projects which is supported by remote shore-based operations and a data interpretation team.

CCUS	Capture	Storage	Transport
	Fuel	Fuel	Fuel
Robotics and Autonomous Systems	1	1	1

Table 50 - CCUS: Robotics and Autonomous Systems Score

Cybersecurity

CO_2 transport and storage must follow the Energy Act 2023[255]. Additionally, the NSTA plays a key role in licensing and regulating offshore CO_2 transport and storage.

AtkinsRealis cyber team have been involved in a carbon capture and storage project to ensure cyber security and resilience is embedded from concept design stage[256].

Given the low level of deployment of CCUS facilities within the UK, the adoption of cybersecurity digital technologies is understood to be moderate across all levels.

CCUS	Capture	Storage	Transport
	Fuel	Fuel	Fuel
Cybersecurity	4	4	4

Table 51 - CCUS: Robotics and Autonomous Systems Score

[254] Sonardyne, 'How to optimise carbon storage monitoring with marine robotics'
[255] Ofgem, 'Carbon capture and storage'
[266] Forrestill (2023), 'Securing our Net Zero future'

Summary and Overall Scoring

With a similar situation to that of geothermal, the number of built CCS/CCUS assets within the UK is minimal and so the adoption of digital technologies is equally low, particularly with robotics technologies.

Geothermal	Production	Storage	Transport
	Fuel (Heat)	Fuel (Heat)	Fuel (Heat)
Artificial Intelligence	2	3	2
Remote Operations	2	3	2
Digital Twins	2	3	3
Robotics and Autonomous Systems	1	1	1
Cybersecurity	4	4	4

Table 52 - CCUS: Overall scoring

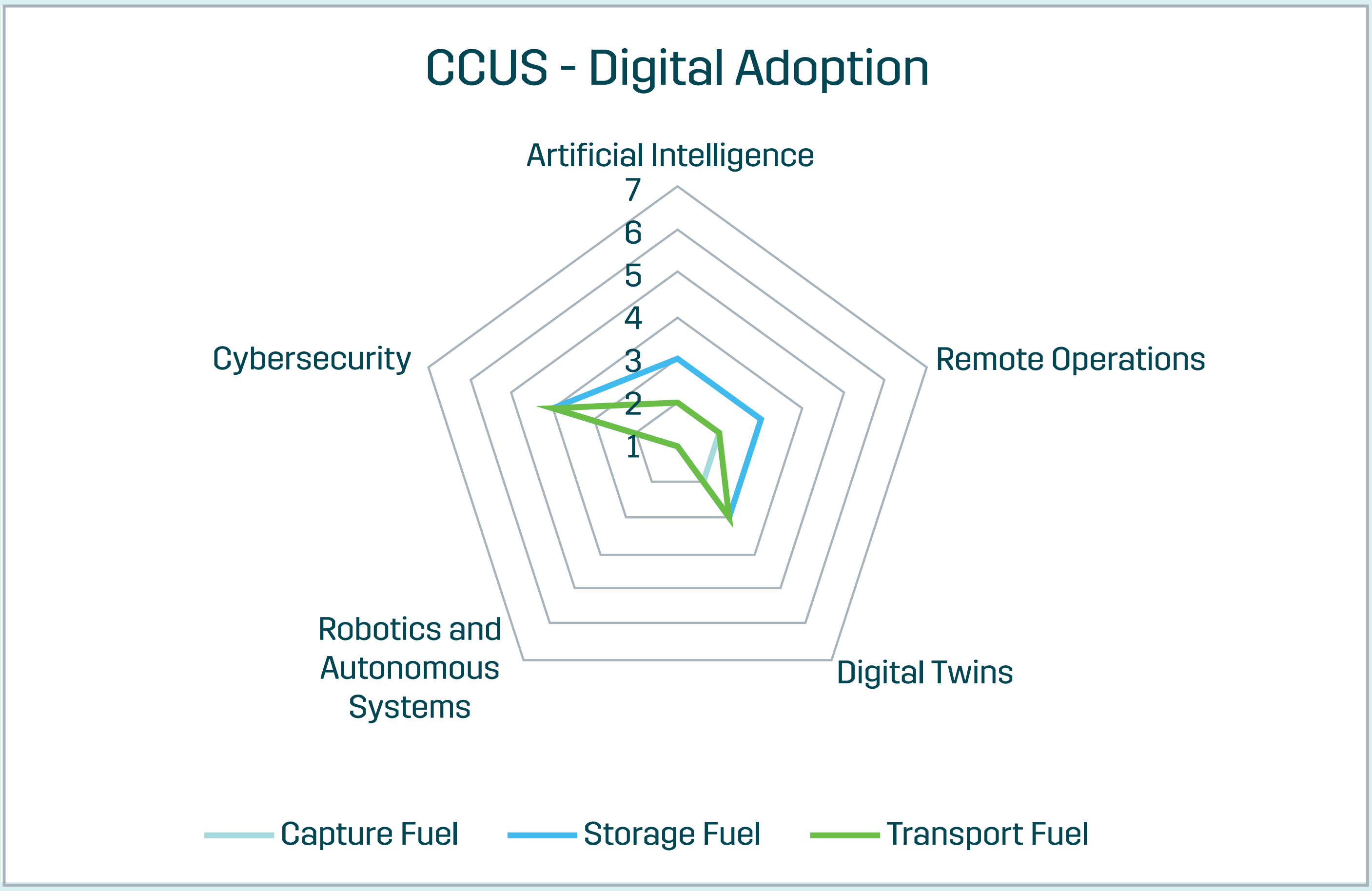


Figure 29 - CCUS Scoring

41. Electricity Network (Transmission, Storage and Utilisation)

The grid is critical to transmit and distribute electricity produced from clean power including solar, wind, wave, tidal, geothermal and nuclear. The grid is undergoing a transition from a small number of large generators input into the high-voltage transmission system, to a complex network with decentralised, microgeneration sources feed into the grid at different times, locations and capacities. This transition requires increased grid flexibility and storage, and demand side flexibility.

Digital technologies are having a large impact on UK grids, but more work is needed. Whilst all players in the UK grid system are incorporating digital technologies, they are all doing so do a different level of maturity. Of the Distributed Network Operators, Electricity North West appears the most advanced with digitalisation a key component of their businesses plan from 2023-2028. They have a goal to be the most digitised and cyber secure DNO in GB. In contrast, SSEN is proceeding cautiously with AI, primarily using it in the analysis of stakeholder and customer feedback.

System operators are looking at digital strategies that incorporate a range of digital technologies. NESO and Energy Systems Catapult are developing a Sector Digitalisation Plan focused on the electricity sector and will map out the digitisation requirements essential to achieve clean power by 2030[257]. Electricity North West published their digitisation strategy in March 2025. NESO, the National Grid and Electricity North West are all investing in research to improve their digital capabilities.

Energy Systems Catapult and Digital Catapult have partnered on a UK-wide initiative to accelerate a digitalised, flexible net-zero energy system - the Digitalising Energy Flexibility programme. The project will explore how innovative tools and programme design can enable multi-vector energy flexibility while addressing barriers to entry for innovators. By developing a “digital toolkit” and complementary acceleration support, the initiative will help to reduce uncertainty, foster collaboration and build a thriving marketplace essential to reach clean power by 2030[258].

AI is being used in the UK grids to enable a more efficient, and resilient grid from improving power management by helping predict energy needs more accurately, to optimising storm response. Digital twins combined with remote sensors are being used by Electricity North West to monitor lines before they become a danger. Robotics is the most immature technology. The only mention found was from the National Grid who is trailing Spot - a high tech robotic quadruped - to carry out inspections to detect potential issues at substations.

Artificial Intelligence

A 2020 report by the accounting firm PwC estimated that by 2030, the incorporation of AI into the energy sector may boost global Gross Domestic Product by up to 4.4% (approximately £3.82 trillion) while helping reduce global carbon emissions by up to 4%.

AI is being used in the UK grids to enable a more efficient, and resilient grid.

Electrical Network	Storage	Transport	Utilisation
	Electricity	Electricity	Electricity
Artificial Intelligence	5	6	5

Table 53 - Electrical Network: Artificial Intelligence Score

[257] NESO, 'Sector Digitalisation Plan'
[258] Digital Catapult, 'Digitalising Energy Programme'

Storage

AI is being used to reduce costs and extend battery life. AI can be used to optimise charging and discharging cycles, preventing overcharging and deep discharging and by analysing current energy consumption and pricing to inform when to discharge and charge.

Transport

In the UK, NESO is responsible for operating the gas and electricity distribution system. NESO is embracing Artificial Intelligence across their entire organisation. They are starting to operationalise their AI models and research and are looking for AI project ideas[259].

National Grid Electricity Transmission operates the transmission system across Great Britain. National Grid Partners have committed to investing £77.3m in AI startups to accelerate a more efficient, resilient and dynamic grid[260].

Utilisation

Commercially, there are six distribution network operators which have been using AI for several years and are carrying out research to incorporate AI into operations. The level or adoption ranges.

- SSEN are using AI to enhance operations, proceeding cautiously and primarily using it in the analysis of stakeholder and customer feedback.
- Electricity North West are currently using AI from optimising storm response to predicting asset conditions. By incorporating AI with their geographic information systems (GIS), they can predict where future vegetation might grow and when it will require attention, helping maintain infrastructure more effectively. Additionally, AI-driven demand forecasting is being used to predict energy needs more accurately, ensuring they can meet customer demands efficiently[261].

Remote Operations

Remote operations and remote monitoring solutions are integral to the UK's electrical network, enabling real-time control, enhanced resilience, and efficient management of grid infrastructure. SCADA (Supervisory Control and Data Acquisition) systems, deployed by entities like UK Power Networks, provide centralised visibility and remote control over substations, allowing operators to manage voltage levels, reroute power during outages, and execute planned switching without on-site intervention.

IoT-enabled smart grids leverage sensors and smart meters to monitor grid health, detect anomalies, and balance demand-supply dynamics, supporting predictive maintenance and reducing outage risks.

Additionally, Active Network Management (ANM) systems optimise renewable energy integration by dynamically adjusting grid operations in response to fluctuations in distributed generation (e.g., solar, wind). These technologies collectively enhance grid reliability, reduce operational costs, and accelerate the UK's transition to a decarbonised energy system.

Electrical Network	Storage	Transport	Utilisation
	Electricity	Electricity	Electricity
Remote Operations	6	7	7

Table 54 - Electrical Network: Remote Operations Score

[259] NESO, 'Innovation'
[260] National Grid (2025), 'National Grid Partners commits $100 million to invest in AI startups advancing the future of energy'
[261] Electricity North West (2025), 'Digitalisation Strategy'

Storage

AI is being used to reduce costs and extend battery life. AI can be used to optimise charging and discharging cycles, preventing overcharging and deep discharging and by analysing current energy consumption and pricing to inform when to discharge and charge.

Transport

A two-year trial of LineVision - a startup in the National Grid Partners investment portfolio - is being conducted on a 275kV circuit between Penwortham and Kirby in Cumbria, UK. The technology has been successfully implemented in the National Grid's networks in the US. LineVision sensors can continuously monitor electricity transmission lines providing real-time data to calculate a 'dynamic line rating'. The rating can be used to maximise the amount of power that can be safely transmitted through the transmission line[262].

Electricity North West is using their active monitoring system - LineSight. Using sensors installed on the network, they can detect and repair damage to overhead lines before it becomes a danger[263].

Utilisation

Electricity North West have implemented an Active Network Management System, which carries out network modelling activities in real time to manage the network, allowing them to optimise flexible loads, distributed generation (DG) units and battery energy storage systems.

Digital Twins

In 2021, NESO launched the Virtual Energy System - a data sharing infrastructure to enable an ecosystem of interconnected digital twins of the entire energy landscape, working in parallel to the physical system. The Virtual Energy System will improve forecasting abilities[264].

Storage

Digital twins are increasingly being deployed in the UK to enhance the efficiency, reliability, and scalability of electrical storage solutions, particularly in the context of renewable energy integration and grid stability. Examples include Highview Power's Carrington Facility which simulates operating conditions to identify performance bottlenecks and optimised energy discharge as well as testing adjustments to the cryogenic systems virtually, reducing physical trial costs and accelerating deployment[265].

Transport

Projects by Electricity North West such as LineSIGHT, Perch and the full rollout of smart meters supported by other industry partners, have allowed them to create a real-time digital twin of their network. This digital twin helps monitor and manage the grid more effectively, ensuring a reliable electricity supply[266].

Utilisation

In collaboration with organisations across the utility sector including NESO and National Grid Electricity Transmission, UK power networks are developing a digital platform called CReDO+ (Climate Resilience Decision Optimiser) which aims to safeguard networks against climate change. By using data across electricity, water, gas and telecommunications, CReDO+ maps out how different infrastructure depend on each other to understand risks that can spread across sectors.

Electrical Network	Storage	Transport	Utilisation
	Electricity	Electricity	Electricity
Digital Twins	5	6	6

Table 55 - Electrical Network: Digital Twins Score

[262] National Grid, 'The innovative and futuristic technologies improving our electricity networks'
[263] Electricity North West (2025) 'Digitalisation Strategy'
[264] NESO, 'Virtual Energy System'
[265] Energy and Sustainability Solutions (2022),'Digital twins heat up the capabilities of energy storage plants'
[266] Electricity North West (2025), 'Digitalisation Strategy'

Robotics and Autonomous Systems

Robotics and autonomous systems are increasingly being deployed across the UK electrical network to enhance safety, efficiency, and asset reliability.

Electrical Network	Storage	Transport	Utilisation
	Electricity	Electricity	Electricity
Robotics and Autonomous Systems	1	6	1

Table 56 - Electrical Network: Robotics and Autonomous Systems Score

Storage

No examples could be found of robotics being actively used within battery / energy storage sites.

Transport

SSEN Transmission has deployed the EXTRM MK4.1 autonomous robot at its Blackhillock HVDC substation-the first of its kind in Scotland-to monitor high-voltage equipment in real time and identify faults or maintenance needs in environments inaccessible to humans when energised[267]. Across these deployments, robotics and autonomous systems are reducing the need for manual inspections in hazardous or hard-to-reach locations, enabling real-time condition monitoring, and supporting predictive maintenance strategies, all while improving safety and operational efficiency for the UK's power networks.

Similarly, National Grid has trialled autonomous mobile robots at interconnector converter sites, using them to regularly collect thermal and acoustic data for early fault detection, and is considering wider deployment following successful pilots[268].

National Grid is also pioneering the use of autonomous drones for overhead line and pylon inspections, including trials of fully automated, beyond-visual-line-of-sight drone operations for corrosion assessment, which can be managed remotely from centralised operation centres[269].

Autonomous drones are being trialled at the Deeside Centre for Innovation for aerial thermal substation inspections and to carry out close-quarter inspection of steelwork and components on the transmission network[270].

UK Power Networks has introduced the Boston Dynamics robot dog "Spot" for inspecting underground power tunnels in London and the southeast, using cameras and advanced thermal imaging to gather data that is then analysed by machine learning algorithms. This approach reduces inspection times, improves accuracy in assessing cable and infrastructure condition, and minimises staff exposure to hazardous environments[271].

Utilisation

Robotics applications with the utilisation of electrical energy from the network is a vast area to explore as this includes both domestic applications (limited/no expected applications) through to industrial facilities where robotics are not expected to be used for the electrical energy use itself, but instead to monitor and inspect the facilities. On this basis, scoring is marked as low.

[267] SSEN (2024), 'New robot to help identify electrical faults rolled out in Blackhillock HVDC Substation - the first of its kind in Scotland'
[268] National Grid (2023), 'Who let the dogs out?'
[269] National Grid (2025), 'National Grid leads the way on cross-industry collaboration with Drones and Robotics Showcase event'
[270] National Grid, 'The innovative and futuristic technologies improving our electricity networks'
[271] Electrical Review (2023), 'UK Power Networks leverages robotic dog to help with tunnel inspections'

Cybersecurity

Network operators manage critical infrastructure, which will have a severe impact if compromised. They incur and are exposed to cybersecurity threats 24/7.

Electricity North West has a large focus on cybersecurity, with an aim to meet and exceed regulatory compliance requirements. They are replacing older tools and platforms with modern cloud-based solutions, reducing the opportunities for attack from cyber criminals and protecting important data. To date, they have initiated 28 projects as part of a comprehensive programme aimed at implementing and embedding practical and lasting interventions across their critical technical and physical estate.

Emerging quantum computing technologies will enable attackers to break into currently highly secure encryption. NESO's SIF R3 Alpha: Network Security in a Quantum Future is a project that creates a management tool to assess quantum threat to the energy network, mapping it to a diverse range of energy systems assets and enabling prioritisation of appropriate mitigations. The project aims to progress the TRL from 2 to 4[272].

By virtue of the network being critical to the UK economy, it is by default high in terms of adoption of cybersecurity-related digital technologies.

Electrical Network	Storage	Transport	Utilisation
	Electricity	Electricity	Electricity
Cybersecurity	7	7	7

Table 57 - Electrical Network: Cybersecurity Score

[272] NESO Energy, 'SIF R3 Alpha: Network Security in a Quantum Future'

Summary and Overall Scoring

Finally, the electrical network has been considered in terms of the transport (transmission and distribution), the storage (e.g. batteries) and utilisation (considering industrial rather than domestic utilisation).

The figure below outlines a high level of adoption for most technologies except for robotics. For powerlines and transmission, the utilisation and adoption are reasonably mature but for utilisation and storage, it is essentially non-existent and arguably not required.

Electrical Network	Storage	Transport	Utilisation
	Electricity	Electricity	Electricity
Artificial Intelligence	5	6	5
Remote Operations	6	7	7
Digital Twins	5	6	6
Robotics and Autonomous Systems	1	6	1
Cybersecurity	7	7	7

Table 58 - Electrical Networks: Overall scoring

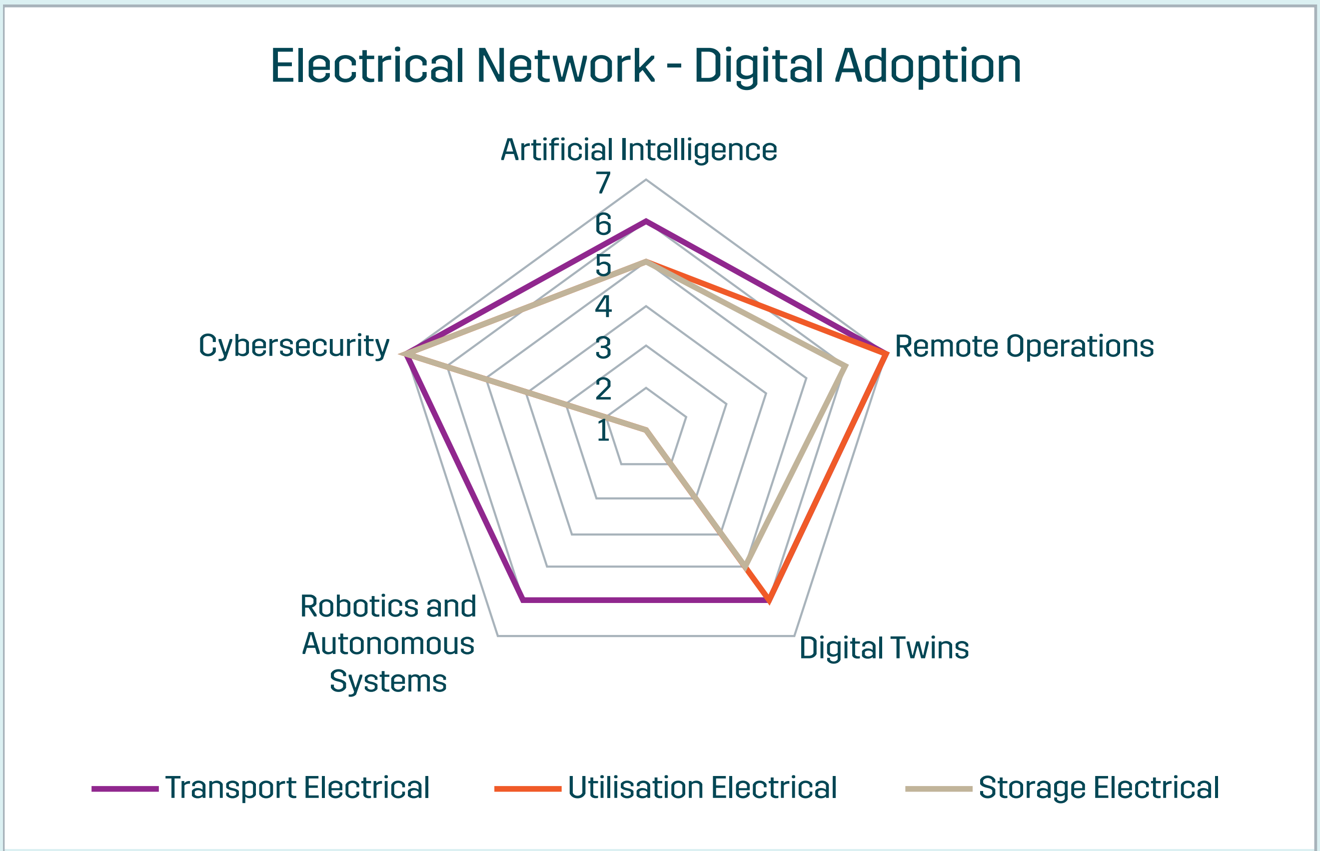


Figure 30 - Electrical Network Scoring

Appendix B - International Comparison

42. Norway

Norway has established itself as a global leader in embedding digital technologies within offshore oil and gas operations. Its approach extends beyond isolated pilots, focusing instead on full-scale integration across live operational environments.

Companies such as Equinor have deployed digital twins, predictive analytics, and remote centres across more than 50 offshore installations. Their Echo system[273] aids real time monitoring and planning, reduces emissions and increases operational efficiency. Similarly, Aker BP has adopted an advanced digital twin strategy in the Yggdrasil development, designed to enable remote operations with minimal offshore staffing[274]. Norway's Krafla field showcases unmanned, digitally operated technology for low-carbon, high-efficiency offshore development using digital twins and AI-driven maintenance[275].

Additionally, Norway has invested in a national data-sharing infrastructure. The NCS DataHub[276] provides a standardised, sector wide platform for operational data, improving performance benchmarking, maintenance planning, and environmental monitoring across the Norwegian Continental Shelf[277].

Norway's focus on organisational change is equally significant. A study[278] analysed how digital technologies are reshaping work structure and management within the petroleum sector, finding that successful digitalisation is not only about technology deployment but also about aligning workflows, trust frameworks, and human factors to ensure safe and efficient operations.

Norway is using AI in offshore operations with a focus on responsible and risk-managed deployment. AI is applied in predictive maintenance, operational optimisation, and safety monitoring. These applications include underwater autonomous vehicles, automated drilling control, and condition monitoring systems[279]. The DNV report outlines Norway's "barrier philosophy," which requires multiple safety barriers for AI-driven systems. Human operators are trained to understand system limitations and can intervene when necessary, ensuring safe collaboration between AI and human teams.

Overall, Norway's offshore sector integrates advanced technology, operational safety principles, workforce transformation, and sector-wide collaboration to implement digital solutions at scale.

Where is Norway Leading?

Norway's competitive edge lies in its ability to integrate digital technologies throughout its operations rather than isolating them within R&D. Norwegian operators have integrated digital technologies across their full operational landscape with companies like Equinor and Aker BP using AI, automation, and advanced analytics in offshore environments to improve efficiency, safety, and reduce emissions.

Equally critical to Norway's success is its investment in workforce upskilling. Workforce development is treated as a strategic enabler, with upskilling programmes coordinated between government, universities, and industry. This approach ensures that operators are not only deploying new technologies, but are also equipped with the capabilities to use, interpret, and improve them over time.

Underlying all of this is a culture of trust and alignment between public and private stakeholders. In Norway, regulators and industry share common goals and timelines, allowing for smoother implementation of digital solutions. This close coordination stands in contrast to more fragmented systems elsewhere, where overlapping mandates and misaligned incentives can slow down progress.

[279] DNV Report 2024-1519 Rev 1, 'State of the Art for Responsible Use of AI in the Petroleum Sector'

Key Enablers

Norway's energy sector is relatively compact and highly integrated, which allows for faster consensus-building and fewer bureaucratic barriers than in larger, more fragmented markets like the UK. Crucially, Norway has invested consistently in the physical and digital infrastructure needed to support advanced energy systems. Subsea data pipelines, national telecoms infrastructure, and integrated monitoring networks provide the backbone for AI and data-driven platforms. These investments have laid the groundwork for seamless connectivity and real-time operational decision-making.

The Norwegian Offshore Directorate plays a proactive role not only in regulating the sector but also in shaping its digital transformation agenda. Its involvement extends to data governance, interoperability standards, and performance reporting, ensuring consistency across organisations and systems. Norway's collaborative culture promotes data sharing and joint investment among operators, suppliers, and regulators, reducing duplication and fostering interoperability. High trust between public and private actors speeds up project delivery, allowing Norway to implement digital solutions faster than countries with fragmented governance.

Together, these enablers reflect a strategic approach to digitalisation, one in which policy, technology, and people are aligned toward system-wide transformation. As a result, Norway continues to set the benchmark for what coordinated digital adoption in offshore oil and gas can look like.

Comparing to UK

Norway and the UK have both been recognised as digital innovation leaders, but their performance diverges significantly when it comes to sustained adoption and system transformation.

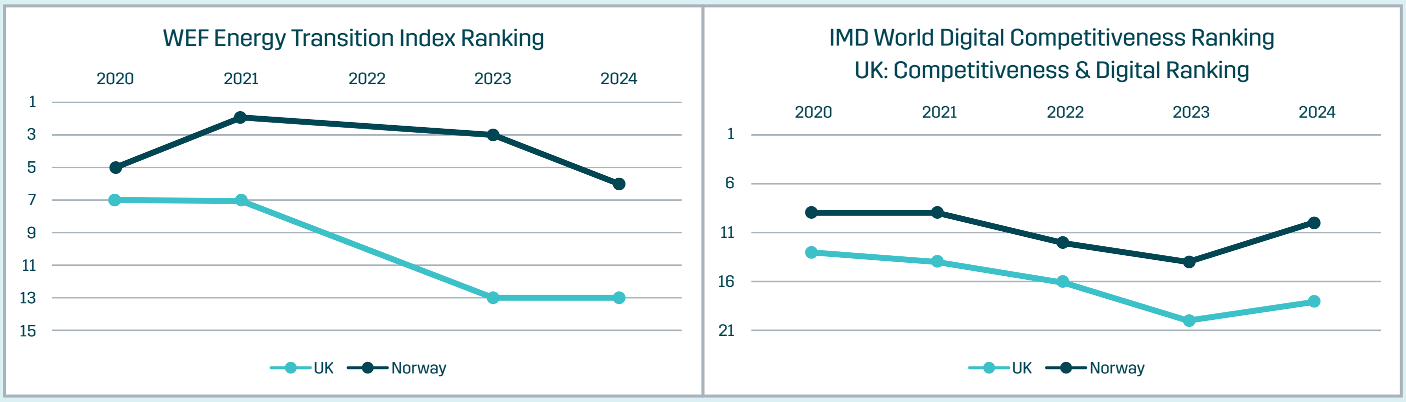
The IMD WDC Ranking places Norway 4th globally, compared to the UK's 18th. Norway excels in sub-rankings related to training, business agility, and IT integration, while the UK continues to struggle with workforce readiness and institutional adaptability. In the WEF Energy Transition Index, Norway holds 3rd place, with strong scores in system performance, energy affordability, and resilience. The UK ranks 13th, hindered by slow progress in affordability, equity, and infrastructure deployment.

Over the past five years, Norway has maintained its position as a global leader, reflecting a stable and cohesive approach to energy system transformation and digital implementation. In contrast, the UK's rankings have declined and stagnated, reflecting a disconnect between digital ambition and delivery.

Metric	UK	Norway	Comparison
IMD Digital Competitiveness 2024 [280]	18th	4th	Norway scores highly on agility, digital skills, and IT integration
ETI Energy Transition Index 2024[281]	13th	3rd	Norway excels in resilience, affordability, and smart energy systems

Table 59 - Comparison of World Rankings (Digital and Energy) - Norway

[280] IMD (2024), 'World Digital Competitiveness Ranking 2024'
[281] World Economic Forum (2024), 'Energy Transition Index 2024'



(Note: WEF Energy Transition Index not published for 2022)
Figure 31 - Comparison between WEF and IMD Ranking (UK vs Norway)

Lessons from Norway for the UK

The Offshore Maturity Survey[282] reveals that many UK organisations face persistent challenges, including weak data strategies, fragmented infrastructure, and limited workforce capability. In contrast, Norway appears to have already addressed many of these issues through a combination of consistent investment, streamlined governance, and collaborative delivery models. While the UK is strong in innovation generation and policy intent, Norway demonstrates long-term execution and system integration, emphasising the importance of launching and embedding digital into the institutional fabric of the energy sector.

The UK, while rich in innovation and early-stage venture activity, struggles to scale and embed these solutions into the core of its offshore operations. This is a critical difference. In Norway, innovation is not an add-on; it is operationalised. Data is not collected and shelved; it is analysed and acted on in real time.

To address the adoption gap, the UK might consider Norway's approach, which includes coordinated delivery, open infrastructure planning, and a workforce strategy based on real-world operational needs. These factors can help turn vision into execution and pilots into platforms.

[282] OEUK (2023), 'Offshore Energy Data and Digital Maturity Survey'

43. Germany

Germany has been a global pioneer of the digital industrial revolution through its leadership in Industry 4.0, a national strategy first introduced at the Hannover Messe in 2011. The vision set by Industry 4.0 was to embed digital technologies such as cyber-physical systems, the Internet of Things (IoT), artificial intelligence (AI), and advanced automation into manufacturing and industrial operations, creating fully connected and intelligent value chains[283].

A distinctive feature of Germany's Industry 4.0 strategy is its focus on horizontal and vertical integration: horizontally across firms and supply chains, and vertically from the shop floor up to enterprise-level planning and management systems. Technologies such as smart factories, predictive maintenance, and digital twin systems are not viewed as isolated innovations but as components of a seamless, interoperable production ecosystem.

A hallmark of Germany's approach has been its systemic and long-term policy support. Initiatives such as Plattform Industrie 4.0[284] coordinate industry, academia, and government efforts to develop technical standards, interoperability frameworks, and digital transformation roadmaps across sectors.

Recent analysis acknowledges that Germany faces emerging risks. Although it retains a leadership position in research and standard setting, there are concerns that industrial-scale standardisation and scaling are progressing more slowly than similar efforts in the United States and China. The so-called "Penguin Effect", where small and medium-sized enterprises (SMEs) hesitate to invest without proven interoperability and standard guarantees, continues to delay widespread digital adoption.

Overall, Germany's approach illustrates a holistic and deliberate national strategy, combining technology development, standardisation leadership, SME support, and international collaboration to enable sustainable, sector-wide digital adoption.

Where is Germany Leading?

Germany's competitive strength in digital adoption lies in its ability to translate innovation frameworks into operational practices across entire sectors. Rather than focusing solely on flagship initiatives, Germany has pursued a systemic approach that embeds digitalisation throughout its industrial base.

A key achievement has been the development of internationally recognised technical standards and interoperability frameworks. Plattform Industrie 4.0 and the RAMI 4.0 model provide blueprints for structured digital transformation, while protocols like OPC UA enable seamless communication across diverse systems[285]. This focus on interoperability ensures that digital integration extends across value chains, not just within individual firms.

Germany has also fostered sector-wide data-sharing ecosystems. The Catena-X Automotive Network enables trusted, decentralised exchange of production and logistics data, strengthening supply chain resilience and operational transparency[286,287].

Workforce transformation is another pillar of Germany's success. Its dual education system has been adapted to meet the needs of a digital economy, promoting data literacy and AI competencies across both vocational and academic pathways. As a result, Germany maintains a workforce capable of implementing and scaling digital technologies across sectors.

Public-private collaboration remains central. Institutions such as the Fraunhofer Society and industrial associations like VDMA work closely with the government to align innovation, regulation, and funding. This coordination accelerates the journey from research to industrial application.

Beyond national boundaries, Germany's leadership role in the Gaia-X project aims to establish federated, sovereign cloud infrastructures that preserve data ownership and interoperability for Europe's industrial base[288,289].

Germany's strategy succeeds because it advances technology within a well-supported ecosystem of standards, skills, and collaboration, ensuring that digital adoption is sustainable, scalable, and sector wide.

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283 Industrie 4.0 in a Global Context
284 Germany Trade & Invest (GTAI), 'Industrie 4.0 Overview'
285 Germany Trade & Invest (GTAI), 'Germany - The World's Leading Industrie 4.0 Nation'
286 Catena-X Automotive Network
287 DLR: Catena-X, 'Digitalisation of the automotive value chain'
288 Gaia-X - About Gaia-X
289 Gaia-X (2025), 'Gaia-X Strengthens European Digital Sovereignty at European Parliament Reception'

Key Enablers

Germany's success in driving digital adoption at scale is rooted in a combination of strategic policy, industrial structure, and cultural factors. Its model demonstrates that long-term planning, broad-based collaboration, and systemic investment are essential for embedding digital technologies across sectors.

Germany's tradition of long-term industrial policy planning is seen as a significant enabler for digital adoption. Initiatives such as the "High-Tech Strategy 2025" embed digitalisation goals across research, education, and industry, ensuring that technological priorities remain consistent across election periods. This continuity gives businesses the confidence to invest in long-term digital transformation programmes.

Germany's focus on SMEs as a core of industrial strength is another key factor. Recognising that the middle-class (Mittelstand) forms the backbone of its economy, Germany has established "Mittelstand 4.0 Competence Centres" to provide free or subsidised support for digitalisation initiatives, ensuring that digital adoption is not limited to large corporations but spreads across the broader industrial landscape.

Research and innovation ecosystems also play a critical enabling role. Institutions such as the Fraunhofer Society and the German Research Centre for Artificial Intelligence bridge the gap between academic research and industrial application, creating testbeds and pilot projects that feed directly into operational rollouts.

Germany's early investment in digital infrastructure, including secure cloud services, industrial 5G networks, and advanced data-sharing platforms, has provided a strong technical foundation for Industry 4.0 integration. Programmes such as Gaia-X ensure that companies can collaborate digitally without compromising data sovereignty or cybersecurity.

Finally, Germany's commitment to standardisation and interoperability has underpinned scalable adoption. Through initiatives like RAMI 4.0 and contributions to international standards bodies, Germany ensures that devices, platforms, and organisations can integrate digitally without being locked into proprietary ecosystems. This reduces risk for companies considering large-scale digital investments and accelerates cross-sector adoption.

Together, these enablers demonstrate that Germany's progress is not simply the result of technological innovation, but of a deliberate and coordinated national effort to build the conditions for widespread, sustainable digitalisation.

Comparing to UK

Germany and the UK have both made significant investments in digital transformation, yet Germany's structured approach to industrial digitalisation has allowed it to surpass the UK in key areas of adoption and competitiveness.

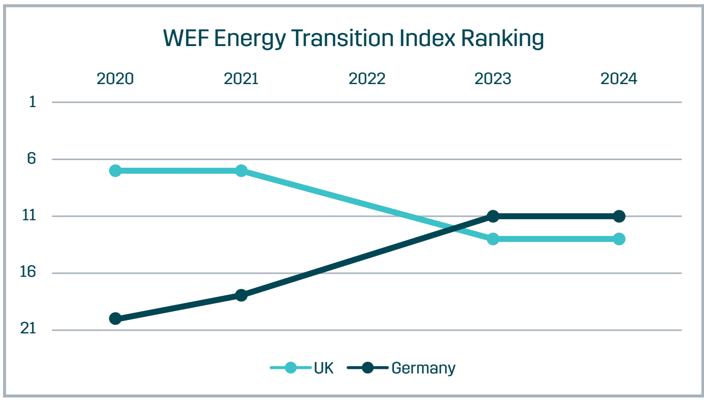
According to the IMD World Digital Competitiveness Ranking 2024, Germany ranks 17th globally, slightly ahead of the UK at 18th.

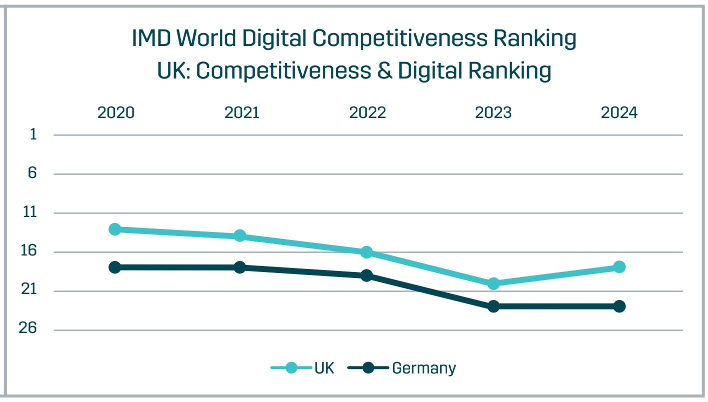
Germany demonstrates stronger performance in sub-rankings such as knowledge infrastructure, technology integration, and future readiness, whereas the UK continues to face challenges in employee training, business agility, and scaling digital innovation. Similarly, in the WEF Energy Transition Index, Germany holds 11th position compared to the UK's 13th.

Metric	UK	Germany	Comparison
IMD Digital Competitiveness 2024[290]	18th	17th	Germany scores higher in knowledge, technology infrastructure, and future readiness
ETI Energy Transition Index 2024[291]	13th	11th	Germany outperforms in system sustainability, energy security, and innovation adoption

Table 60 - Comparison of World Rankings (Digital and Energy) - Germany

[290] IMD (2024), 'World Digital Competitiveness Ranking 2024'
[291] World Economic Forum (2024), 'Energy Transition Index 2024'





(Note: ETI not published for 2022.)
Figure 32 - Comparison between WEF and IMD Ranking (UK vs Germany)

Germany's higher ranking reflects its progress in energy system sustainability, technological innovation, and long-term resilience planning.

Over this period, Germany has shown consistent improvement in energy transition performance with a similar trend to the UK in terms of overall digital competitiveness, but lower in overall ranking. At the same time, Germany has steadily improved its ETI performance, reaching 11th place globally by 2024, compared to the UK's 13th position.

Sub-ranking analysis from the IMD WDC Ranking shows that, in the Knowledge category, Germany excels through high levels of R&D expenditure and the strength of its university education system. In Technology, Germany benefits from advanced ICT development and a robust legal environment that supports innovation. Furthermore, in Future Readiness, Germany demonstrates strong agility of companies, a high level of cybersecurity preparedness, and adaptive organisational attitudes, positioning it favourably against global peers.
By contrast, the UK remains in an overall stronger position than Germany which highlights the strength in the UK, but the need to learn from others.

Lessons from Germany for the UK

Germany's experience highlights the importance of building strong foundations for digital adoption, beyond isolated innovation initiatives. For the UK to close its widening gap, several lessons can be drawn.

One of the defining features of Germany's approach is its consistent, long-term policy framework. Strategies such as Industry 4.0 and the High-Tech Strategy 2025 have provided companies with stable signals to invest confidently in digital transformation, rather than navigating shifting priorities. Support for small and medium-sized enterprises (SMEs) through establishment of Mittelstand 4.0 Competence Centres has ensured that digital adoption is not confined to larger corporations but extends across its industrial fabric, helping smaller companies transition effectively.

Prioritising interoperability and open standards through platforms such as Plattform Industrie 4.0, companies have provided access to common frameworks that reduce integration risks and foster sector-wide collaboration.

Workforce development has been treated as an ongoing strategic priority. Germany's dual education system, coupled with its investment in digital reskilling, ensures that its workforce remains capable of operating and optimising advanced digital systems, maintaining industrial competitiveness over time.

For the UK, replicating these conditions, particularly enhancing SME digital support, embedding interoperability, and investing systematically in workforce skills and education, will be critical to improving its digital adoption performance and ensuring long-term industrial resilience.

44. United States of America

The United States is a global leader in digital technology adoption across its energy sector, with strong integration in the electricity grid, renewables, and oil and gas industries. Utilities are deploying smart meters, advanced analytics, and AI-driven grid management to optimise operations and support renewable integration[292].

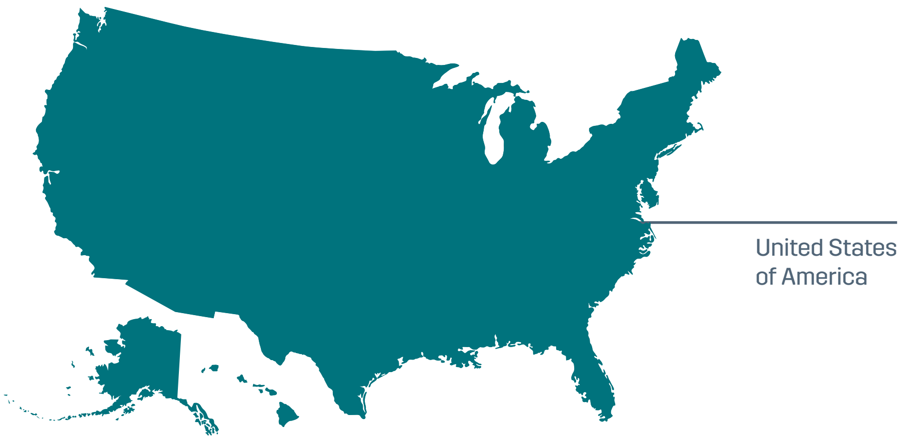
In oil and gas, digitalisation is advanced, with cloud computing, AI, and robotics streamlining exploration, production, and predictive maintenance. Sectors such as nuclear[293], hydrogen[294], and carbon capture[295] are seeing moderate adoption, leveraging digital twins, process optimisation, and real-time monitoring to enhance safety and efficiency. Early-stage digitalisation is also underway in geothermal, wave, and tidal energy, focusing on resource mapping and pilot projects[296].

Federal initiatives are central to this transformation. The Department of Energy's Grid Modernisation Initiative[297] funds research, deployment, and workforce training in digital energy technologies. Cybersecurity is a major focus, with DOE programs and fellowships aimed at protecting increasingly connected energy systems[298]. Industry partnerships with technology leaders such as Microsoft, Google, and Shell are accelerating cloud-based operations, data analytics, and the development of AI-powered virtual power plants.

Research institutions and national laboratories are also key players, piloting innovative projects such as blockchain-based energy trading[299] and AI-driven permitting tools[300]. These efforts are creating new opportunities for efficiency gains, grid resilience, and consumer empowerment.

The US approach is characterised by strong collaboration between government, academia, and industry. Initiatives led by the Department of Energy and national laboratories, such as NREL's Autonomous Energy Systems program[301] bridges robotics, artificial intelligence, and energy engineering to deliver deployable solutions at scale. Support from the Department of Energy's Office of Fossil Energy and Carbon Management further accelerates offshore digitalisation.

Despite these advances, challenges remain. Modernising legacy infrastructure is costly and complex, and the growing reliance on digital systems heightens cybersecurity risks. There is also a pressing need for skilled workers in digital and cybersecurity roles, as well as solutions for integrating vast and fragmented energy data. Nevertheless, ongoing investment, innovation, and public-private collaboration continue to position the US as a global leader in the digital transformation of the energy sector.



[292] U.S. Department of Energy, 'Grid Modernisation Initiative'
[293] World Nuclear Association (2024), 'Nuclear Power in the USA'
[294] Energy.Gov, 'Hydrogen Program'
[295] Energy.Gov, 'Carbon Management'
[296] National Renewable Energy Lab (NREL)
[297] DOE Grid Modernisation Laboratory Consortium
[298] Energy.Gov, 'Office of Cybersecurity, Energy Security, and Emergency Response'
[299] Oak Ridge National Laboratory, 'Energy Science and Technology Directorate'
[300] Pacific Northwest National Laboratory, 'PermitAI'
[301] NREL, 'Autonomous Energy Systems'

Where is the USA Leading?

The USA is leading in several key areas of digital technology adoption within the energy sector, positioning itself at the forefront of the industry's transformation. One of the most prominent areas is grid modernisation and smart energy solutions. Utilities across the US are investing heavily in advanced metering infrastructure, demand response systems, and automated grid control. The US energy sector is also rapidly deploying IoT sensors and connected devices for remote asset monitoring, predictive maintenance, and real-time data analytics.

Artificial Intelligence (AI) and machine learning are areas where the US excels. AI is widely used for forecasting energy demand, optimising equipment operation, and enabling predictive maintenance. Major US tech companies, including Google, Amazon, and Microsoft, are investing in AI-driven demand response and cloud-edge computing to further enhance grid flexibility and reliability.

A key strength lies in the widespread adoption of robotics for remote offshore inspections, subsea maintenance, and autonomous monitoring. Companies such as Chevron and ExxonMobil have successfully moved beyond pilot programmes to deploy autonomous underwater vehicles (AUVs) and robotic platforms as standard tools for offshore oil and gas operations[302].

In the renewables sector, particularly offshore wind, the United States excels in the development and application of robotic blade inspection systems and autonomous drones for cable monitoring and maintenance. Programmes such as ARPA-E's ATLANTIS initiative have supported the growth of intelligent autonomous systems specifically designed for harsh marine environments.

A critical advantage is the ability to rapidly transition technologies from research environments into real-world deployment. National programmes like the National Robotics Initiative 3.0 fosters interdisciplinary collaboration across academia, government laboratories, and industry. This tight feedback loop accelerates the scaling of robotics solutions, reducing time-to-impact compared to slower-moving regulatory or industrial frameworks seen elsewhere.

The United States benefits from a strong culture of field trials and iterative improvement, particularly supported by agencies like the Department of Energy (DOE). Initiatives run by the DOE's Office of Fossil Energy and Carbon Management have provided testbeds for robotics deployment in offshore oil platforms and renewable infrastructure projects[303]. Together, these strengths ensure that robotics are not seen as experimental add-ons but as integral operational technologies embedded into the everyday running of energy systems.

In summary, the USA leads in digital grid modernisation, IoT integration, robotics, and AI and machine learning applications. These advancements are underpinned by strategic investments, regulatory support, and partnerships with leading technology firms, positioning the US as a global innovator in digital energy transformation.

Key Enablers

Several systemic enablers explain why the United States has achieved leadership in the deployment of advanced robotics across oil, gas, and renewables sectors.

A crucial driver is the scale and consistency of public R&D funding. Long-running programmes like the National Robotics Initiative[304] provide multi-year support that allows robotics technologies to mature beyond early-stage research[305]. Complementing this, targeted investments through ARPA-E[306] and the DOE's initiatives have focused specifically on energy sector challenges, ensuring that solutions are tailored for offshore, hazardous, and remote operational contexts.

Another enabler is the United States' strong innovation ecosystem, which connects national laboratories, top-tier universities, start-ups, and major corporations. Cross-disciplinary centres, such as those run by the National Renewable Energy Laboratory (NREL)[307], integrate robotics with artificial intelligence, materials science, and energy engineering to accelerate technology development.

Finally, cultural factors, including a national emphasis on entrepreneurship, risk-taking, and technological adoption, help new technologies reach commercial viability more rapidly than in regions with more conservative industrial cultures.

Together, these enablers have allowed the United States to position itself at the forefront of integrating digital technology into operational practice across the energy value chain.

[302] Ocean Infinity (2020), 'Ocean Infinity to support ExxonMobil in Guyana'
[303] IFRF (2025), 'DOE Announces multiple carbon management initiatives'
[304] National Robotics Initiative
[305] NSF 21-559: National Robotics Initiative 3.0
[306] ARPA-E ATLANTIS Programme
[307] NREL: Autonomous Energy Systems

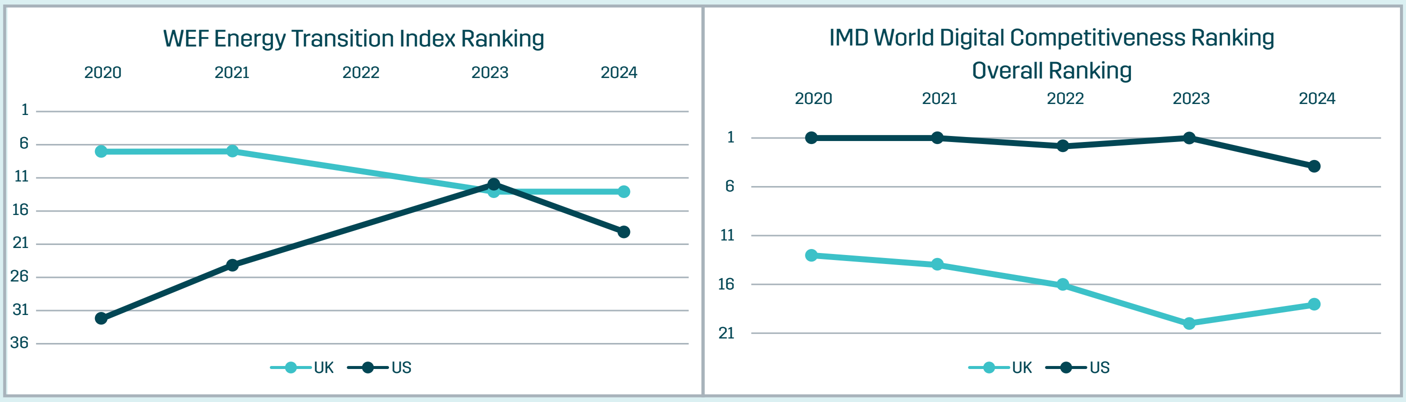
Comparing to UK

The United States and the United Kingdom have both invested heavily in digitalisation and energy transition strategies, yet their current standings reveal distinct differences in focus and outcomes.

The most recent 2024 rankings offer a clear snapshot of the gap between the two countries:

Metric	UK	US	Comparison
IMD Digital Competitiveness 2024[308]	18th	4th	The US leads in technology infrastructure, cyber-readiness, and R&D investment.
ETI Energy Transition Index 2024[309]	13th	19th	The UK leads in renewable energy adoption, energy equity, and policy support.

Table 61 - Comparison of World Rankings (Digital and Energy) - USA



(Note: ETI was not published for 2022.)
Figure 33 - Comparison between WEF and IMD Ranking (UK vs US)

308 IMD (2024), 'World Digital Competitiveness Ranking 2024'
309 World Economic Forum (2024), 'Energy Transition Index 2024'

In digital competitiveness, the United States ranks 4th globally, far ahead of the United Kingdom at 18th. The US excels in sub-rankings such as technology integration, research intensity, cybersecurity, and business agility, while the UK continues to struggle with employee training, adaptability, and digital skills deployment[310].

Conversely, in the energy transition space, the United Kingdom holds a stronger position, ranking 13th globally compared to the United States at 18th. The UK benefits from more advanced renewable energy adoption, policy frameworks promoting system resilience, and higher energy equity, although the US has made notable improvements in recent years[311].

Throughout the past 5 years, the United States has consistently maintained a top global position in digital competitiveness, supported by deep investment in R&D, robust technology ecosystems, and a strong culture of innovation. The United Kingdom's digital competitiveness, in contrast, has steadily declined, falling from 13th in 2020 to 18th in 2024.

In WEF Energy Transition Index, the United Kingdom has remained ahead, although the United States has improved significantly, moving from 32nd place in 2020 to 18th in 2024. The UK's policy stability, renewable energy targets, and energy equity frameworks have supported its Energy Transition Index performance.

This divergence highlights a critical gap between the two countries. The United States leads in digital infrastructure, robotics-enabling technologies, and operational digitalisation, providing a strong foundation for future automation across the energy sector. Meanwhile, the United Kingdom maintains a leadership position in clean energy transformation but must urgently strengthen its digital competitiveness if it is to fully capitalise on emerging technologies such as advanced robotics and autonomous systems.

Lessons from US for the UK

One of the major gaps highlighted in the UK's offshore sector is the lack of digital workforce skills, with only around 30% of organisations confident in their capabilities[312]. In contrast, the United States has embedded workforce development into national programmes like the National Robotics Initiative and the Energy Robotics and Autonomous Systems Programme, ensuring a steady supply of engineers, data scientists, and robotics specialists.

The UK's fragmentation of digital strategies across organisations is another key challenge. The United States addresses this by fostering strong collaboration between national laboratories, universities, private companies, and federal agencies.

Programmes such as ARPA-E's ATLANTIS have demonstrated how coordinated investment drives operational adoption.

Infrastructure and data-sharing weaknesses identified in the UK seem to be better addressed in the United States. Investment in interoperable cloud platforms, cybersecurity frameworks, and offshore operational technologies has enabled more seamless deployment of robotics and automation. Flexible regulatory pathways allow US companies to test, validate, and scale robotics systems faster than in the UK, where rigid approval processes often delay operational integration.

Finally, while the UK is strong in running pilot projects, the United States has consistently moved beyond piloting into full-scale operational deployment, narrowing the gap between research and real-world impact.

By focusing on workforce development, strategic infrastructure planning, ecosystem collaboration, and regulatory agility, the US provides a practical model for how the United Kingdom could strengthen its own digital adoption trajectory.

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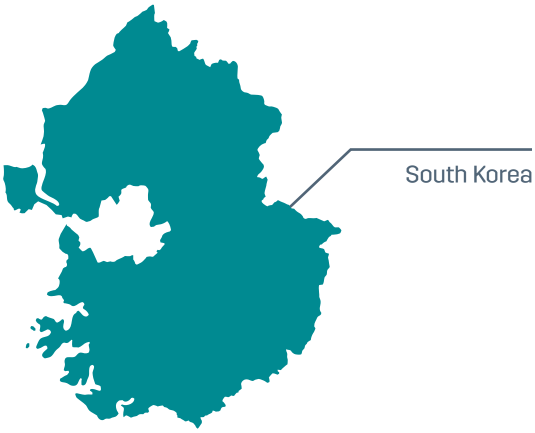
[310] IMD World Digital Competitiveness Ranking 2024
[311] World Economic Forum's Energy Transition Index 2024
[312] OEUK (2023), 'Offshore Energy Data & Digital Maturity Survey 2023'

45. South Korea/Japan

South Korea and Japan are emerging as global leaders in nuclear energy innovation and the application of robotics in high-risk environments. Both countries, driven by energy security concerns and constrained domestic fossil fuel availability, have made strategic investments in developing resilient, low-carbon nuclear infrastructure, while simultaneously pushing the boundaries of automation in reactor operations and decommissioning.



South Korea's nuclear strategy is anchored by the 10th Basic Plan for Electricity Supply and Demand[313], which aims to increase the share of nuclear power generation to stabilise baseload capacity alongside intermittent renewables. This includes the continued operation of older plants, the construction of new reactors, and support for next-generation systems. The Korean-developed APR-1400 reactor has been successfully deployed abroad, most notably at the Barakah Nuclear Power Plant in the UAE, signalling South Korea's emergence as a credible nuclear exporter[314].

In contrast, Japan's nuclear policy has evolved significantly since the 2011 Fukushima Daiichi accident. While public sentiment initially forced large scale shutdowns, Japan has recently announced its Green Transformation (GX) strategy[315], which calls for the restart of existing plants, the extension of reactor lifespans beyond 60 years, and the development of advanced nuclear technologies such as High-Temperature Gas-cooled Reactors (HTGRs) and next-generation light water reactors[316]. Japan is also deeply involved in fusion research, participating in the ITER project[317] and investing in domestic capabilities in materials science and simulation modelling[318].

Together, South Korea and Japan represent complementary models of innovation: Korea advancing as a nuclear systems exporter with integrated digital and robotic capability, and Japan focusing on safety-driven R&D, robotics specialisation, and long-term reactor innovation. Both approaches offer critical insights for nations seeking to modernise their nuclear sectors with resilient, digitally integrated infrastructure.

313 Ministry of Trade: Key Contents of the 10th Basic Plan on Electricity Supply and Demand
314 Korea Hydro & Nuclear Power: APR-1400 deployment
315 Overview of Japan's Green Transformation (GX)
316 Japan sees greater future role for nuclear energy
317 ITER: International Tokamak Research
318 JT-60A org, 'What is JT-60SA?'

Where is South Korea/Japan Leading?

South Korea and Japan have positioned themselves at the forefront of innovation in nuclear energy and robotics, each developing strengths that set global benchmarks for safety, automation, and technical advancement.

Both countries have invested heavily in robotics for nuclear applications, particularly in hazardous or post-accident environments. Japan, following the Fukushima disaster, has become a global reference point for robotics in decommissioning. The International Research Institute for Nuclear Decommissioning (IRID) has developed radiation hardened robots, including crawler bots, snake-like articulated arms, and aerial drones, for tasks such as internal inspection, fuel retrieval, and debris removal within high-radiation zones[319]. Companies like Toshiba and Hitachi have played leading roles in developing these technologies.

South Korea, meanwhile, has focused on incorporating robotics into standard reactor operations and decommissioning. The Korea Atomic Energy Research Institute (KAERI) has led projects on robotic manipulators, remote inspection systems, and AI-supported control systems to assist in dismantling and waste handling[320]. The use of digital twins and virtual reality (VR) simulators is also expanding, enabling improved training for remote operators and predictive planning for decontamination processes.

Japan, for its part, has focused on sensor networks, autonomous monitoring, and real-time system simulations to enhance operational safety and post-disaster resilience.

Taken together, South Korea leads in scalable nuclear delivery and lifecycle digitalisation, while Japan leads in safety innovation, robotics, and next-generation R&D. These complementary strengths position both countries as global leaders in integrating nuclear energy with advanced automation, demonstrating how technical excellence and strategic vision can be harnessed to meet both national and international energy goals.

Key Enablers

The success of South Korea and Japan in advancing nuclear energy and robotics is underpinned by a combination of long-term strategic planning, coordinated institutional delivery, and a culture of innovation that integrates research and operational deployment.

In South Korea, energy policy is tightly interwoven with industrial development. The Korea Atomic Energy Research Institute (KAERI), which functions not only as a research hub but also as a development and implementation centre, is progressing digital twins, VR simulators, and remote robotics enabling South Korea to embed digital innovation across the full reactor lifecycle, from operations to decommissioning.

Several shared enablers underpin both countries' success. Consistent long-term public investment has created an environment of policy stability. National research institutions are closely tied to industry, ensuring that innovations move rapidly from the lab to deployment. Emerging technologies such as AI, robotics, and digital modelling are embedded directly into national energy strategies. Moreover, both countries have developed strong regulatory-industry alignment, allowing them to operationalise R&D outputs efficiently and, in South Korea's case, scale those into international markets. These factors have combined to foster a culture of reliability, innovation, and resilience, positioning South Korea and Japan as global leaders in nuclear digitalisation and robotic automation.

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[319] IRID: Robotics for Fukushima Decommissioning
[320] KAERI: Nuclear Robotics and Remote Systems

Comparing to UK

The most recent 2024 rankings provide a high-level snapshot of the digital and energy transition positioning of the United Kingdom, South Korea, and Japan. While the UK performs well in the energy transition domain, it is far behind South Korea, whilst out-performing Japan in terms of digital competitiveness.

South Korea's sixth place in the IMD Digital Competitiveness Ranking is underpinned by strong performance in future readiness, technology integration, and government responsiveness to digital change. It excels in digital training infrastructure and business agility, areas where the UK has persistently struggled. Japan, while ranked lower at 31st, continues to show strength in scientific output, cybersecurity, and robotics deployment, though its national digital strategy has been less agile in recent years.

In contrast, the UK performs more favourably in the WEF Energy Transition Index, maintaining a stable 13th place due to its leadership in renewable deployment, grid flexibility, and policy commitment. Japan and South Korea, although improving, rank 26th and 23rd respectively. South Korea has climbed from 48th in 2020 to 23rd in 2024, thanks to its national push on nuclear digitalisation and smart grid upgrades. Japan, meanwhile, has faced a slower transition due to nuclear restart delays and higher fossil fuel reliance, although its innovation in advanced nuclear and fusion R&D is world leading.

Over the past five years, South Korea has shown a remarkable rise in energy transition performance while also establishing itself as a global digital leader with a consistent top 10 position in the IMD Digital Competitiveness Index. Japan, despite more modest progress, maintains strength in innovation and robotics but continues to face systemic hurdles in both digital transformation and energy system reform.

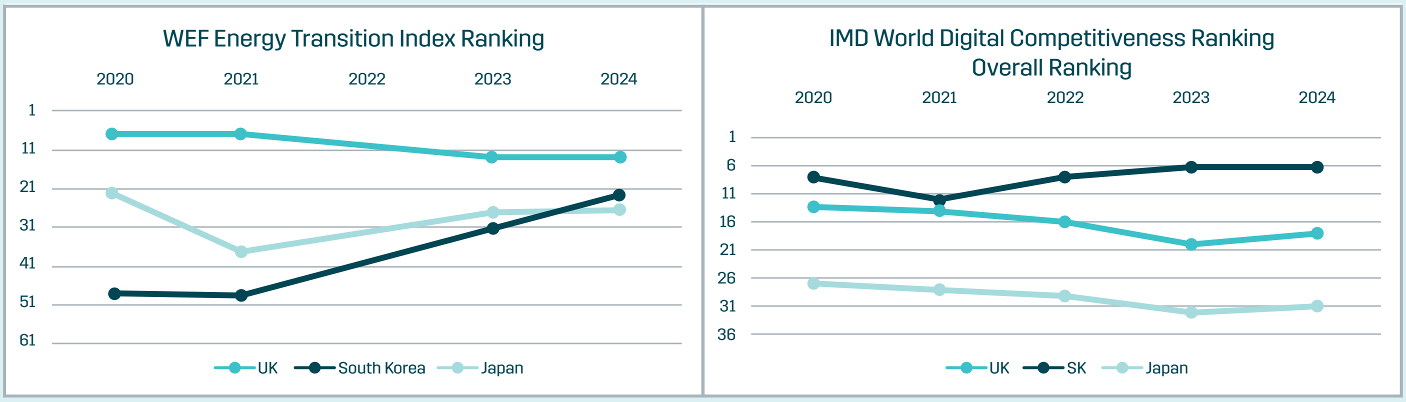
By contrast, the UK has sustained a strong position in energy transition, consistently ranking in the global top 15 due to leadership in renewables, grid equity, and policy frameworks. However, its digital competitiveness has declined, falling from 13th in 2020 to 18th in 2024.

This divergence reinforces the urgent need for the UK to translate its clean energy ambitions into digitally enabled execution. South Korea's integration of digital systems into nuclear operations and Japan's world-leading safety robotics offer practical models. For the UK to fully realise the benefits of its energy transition leadership, it must close its digital capability gaps, particularly in infrastructure investment, workforce development, and applied technology adoption across the energy sector.

Metric	UK	South Korea	Japan	Comparison
IMD Digital Competitiveness 2024[321]	18th	6th	31st	South Korea outperforms the UK across sub-factors like agility, R&D, and ICT integration.
ETI Energy Transition Index 2024[322]	13th	23rd	26th	The UK leads in renewable deployment, equity, and policy support.

Table 62 - Comparison of World Rankings (Digital and Energy) - South Korea / Japan

[321] IMD (2024), 'World Digital Competitiveness Ranking 2024'
[322] World Economic Forum (2024), 'Energy Transition Index 2024')



(Note: ETI was not published for 2022.)
Figure 34 - Comparison between WEF and IMD Ranking (UK vs South Korea and Japan)

Lessons from South Korea and Japan for the UK

South Korea ranks 6th in the IMD World Digital Competitiveness Index 2024, supported by a highly skilled digital workforce, national investment in technical training, and institutional collaboration across industry, academia, and government. Japan, although ranked 31st, still benefits from its deep experience in robotics, scientific R&D, and safety-critical technology, much of which has been operationalised in nuclear contexts.

South Korea's high level of coordination across agencies and energy operators allows it to align innovation, regulation, and deployment. Similarly, Japan's energy institutions demonstrate strong cohesion between research centres and operational deployment bodies. This contrasts with the UK's often siloed efforts, where delivery can be impeded by unclear ownership and inconsistent planning.

On the infrastructure side, the UK lags in digital systems maturity. The Digital Maturity Survey results show that more than half of UK organisations lack integrated digital platforms or data-sharing capabilities[323]. South Korea, meanwhile, has embedded AI, automation, and digital twins into daily operations in its nuclear and industrial sectors. Japan's robotics programmes are world leading in remote and hazardous environments, translating into scalable technologies for inspection, repair, and decommissioning.

Despite these gaps, the UK remains ahead in energy transition performance, however, the UK's ability to sustain this leadership is limited by its digital underperformance, with weak business agility, training infrastructure, and long-term investment holding back sector-wide transformation[324].

In summary, South Korea and Japan provide concrete examples of how to move from digital ambition to embedded operational capability. Their success stems from unified strategies, workforce development, and long term institutional alignment, elements the UK must prioritise if it is to strengthen digital adoption across its energy sector.

[323] OEUK, 'Offshore Energy Data & Digital Maturity Survey 2023'
[324] IMD World Digital Competitiveness Ranking 2024

46. Singapore

Singapore has strategically embraced digitalisation to enhance its energy infrastructure, aiming for a more sustainable, efficient, and resilient energy future. Central to this vision is the Singapore Energy Story[325], which outlines the nation's commitment to transforming its energy sector through innovation and technology.

A fundamental aspect of this transformation is the nationwide rollout of Advanced Electricity Meters, managed by SP Group, with the goal to equip all households and businesses with smart meters by 2026. These meters supply consumers with detailed information about their energy consumption, encouraging more informed and efficient energy use[326].

The Energy Market Authority (EMA) and SP Group are piloting the Grid Digital Twin[327] to enhance grid reliability and incorporate renewable energy. The virtual model of the physical grid enables real-time monitoring and predictive maintenance.

In addressing the challenges of energy storage, EMA and SP Group have initiated a pilot project for an Ice Thermal Energy Storage System, storing energy as ice during off-peak hours, to then be used for cooling during peak demand, enhancing grid flexibility and resilience[328].

Ensuring the cybersecurity of this digital infrastructure is paramount. The Cybersecurity Code of Practice for Critical Information Infrastructure (CCoP 2.0) mandates stringent cybersecurity measures for operators of essential services, safeguarding the energy sector[329].

Singapore exemplifies a holistic approach to digitalising its energy infrastructure, seamlessly integrating advanced technologies to meet sustainability goals.

Where is Singapore Leading the way?

Singapore's greatest strength in digital energy transformation lies in its ability to integrate advanced technologies into core energy infrastructure, not as standalone pilots, but as nationally coordinated, operational solutions. From smart meters to predictive grid analytics, these systems are embedded directly into how the country plans, operates, and governs its energy system.

Together, these initiatives show that Singapore's success lies not only in innovation but in its ability to deploy these technologies systemically, ensuring that energy digitalisation supports both long-term sustainability goals and real-time operational excellence.

Key Enablers

Singapore's success in digitalising its energy infrastructure is underpinned a long-term strategy, cross-agency coordination, strong regulatory frameworks, and deliberate innovation policy.

A major driver is Singapore's whole-of-government coordination. The Energy Market Authority (EMA), as part of the broader Smart Nation initiative, aligns digitalisation efforts across ministries, utilities, and technology providers. This ensures that digital technologies, such as AI, smart meters, and grid twins, are not deployed in isolation but serve a unified energy transition strategy.

Public private collaboration is another critical enabler. SP Group, the national grid operator, plays a central role not just in energy delivery but in R&D, data infrastructure, and innovation testing. Its partnership with EMA on the Digital Grid and Grid Digital Twin exemplifies how operational knowledge and policy objectives are merged into joint platforms.

Singapore also benefits from consistent public sector investment in applied R&D. Research institutions such as ERI@NTU and the Solar Energy Research Institute of Singapore (SERIS) work closely with industry to bring emerging technologies, like solar forecasting, battery analytics, and AI-driven energy management, into deployable, commercial forms.

Regulatory agility allows these innovations to move quickly from pilot to deployment. Singapore's regulators support experimentation but also provide a clear roadmap for scale-up.

Singapore's emphasis on cybersecurity and digital trust ensures that technological advancement is underpinned by resilience. The Cybersecurity Code of Practice for Critical Information Infrastructure (CCoP 2.0) sets internationally recognised standards for energy sector protection, giving confidence to investors and operators alike.

325 EMA - Singapore Energy Story
326 Smart Energy International (2021), 'Why Singapore needs to get smart about metering'
327 EMA - Grid Digital Twin Overview
328 EMA - Thermal Energy Storage System at Electricity Substation
329 CSA - Cybersecurity Code of Practice for Critical Information Infrastructure (CCoP 2.0)

Metric	UK	Singapore	Comparison
IMD Digital Competitiveness 2024[330]	18th	1st	Singapore leads in regulatory agility, digital integration, and business adaptability.
ETI Energy Transition Index 2024[331]	13th	64th	The UK performs better in energy equity, renewables deployment, and system resilience.

Table 63 - Comparison of World Rankings (Digital and Energy) - Singapore

Comparing to UK

Singapore and the United Kingdom both exhibit high ambition in digital transformation and energy transition. However, their performance diverges in global benchmarking frameworks, which reflect distinct national approaches and structural contexts.

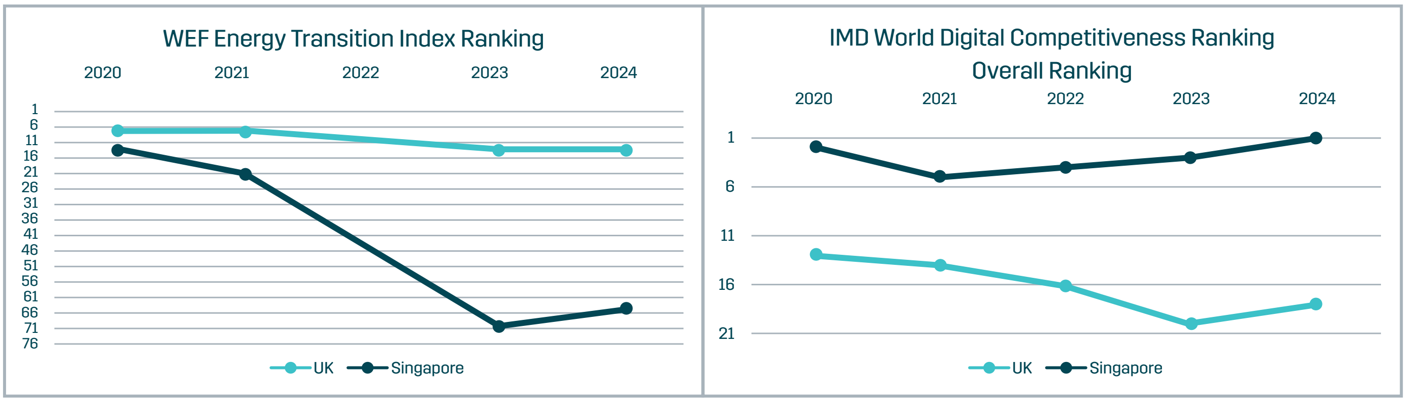
The most recent 2024 rankings offer a clear snapshot of the differences between the two countries:

In digital competitiveness, Singapore holds the highest position, while the UK ranks 18th. Singapore's leadership is driven by high scores in technology integration, future readiness, scientific concentration, and training & education. Conversely, the UK continues to struggle in areas such as employee training, business agility, and investment in digital infrastructure.

In contrast, the UK maintains a far stronger position in the Energy Transition Index. Ranking 13th globally, the UK benefits from robust renewable energy policies, affordability mechanisms, and regulatory frameworks that support grid decarbonisation. Singapore ranks very low, 64th out of 120, largely due to structural limitations such as limited domestic energy resources and a high dependence on imported fuels.

Throughout the past five years, Singapore has consistently ranked first or second in digital competitiveness, underpinned by a cohesive regulatory framework, national smart grid planning, and integrated public-private innovation ecosystems. The UK, by contrast, has seen a decline from 13th to 18th, with stagnation in workforce digital capabilities and fragmented institutional delivery holding back broader adoption.

In the energy transition space, the UK has remained ahead, although Singapore has steadily declined due to a combination of structural, policy, and external factors. The country's heavy reliance on imported natural gas, currently accounting for over 95% of electricity generation, has created both economic and security risks that undermines emissions reduction efforts and exposes Singapore to volatile global gas prices.



(Note: ETI was not published for 2022.)
Figure 35 - Comparison between WEF and IMD Ranking (UK vs Singapore)

330 IMD (2024), 'World Digital Competitiveness Ranking 2024'
331 World Economic Forum (2024), 'Energy Transition Index 2024'

Lessons from Singapore for the UK

A major weakness identified in the UK's offshore energy sector is the lack of confidence in workforce digital skills, with only a minority of organisations feeling adequately equipped[332]. In addition, the UK suffers from fragmented implementation of digital strategies, with many organisations lacking coordination between leadership, infrastructure teams, and data managers.

Singapore, in contrast, has embedded digital capability development into national policy, linking education, industry partnerships, and grid operations to ensure a pipeline of technically proficient talent[333]. Singapore also has a far more aligned digital strategy through centrally coordinated initiatives like the Digital Grid and Smart Grid Taskforce, which align national planning, utility operations, and innovation funding under a shared strategic vision.

Finally, while the UK shows strength in piloting new tools, it continues to struggle with scaling up from demonstration to full operational deployment. Singapore, by contrast, ensures that innovation is embedded into live systems early, accelerating the shift from testing to transformation.

In summary, Singapore has overcome many of the barriers facing the UK. By embedding digital policy within national energy planning, coordinating institutional delivery, and securing foundational trust through cybersecurity and skills investment, Singapore offers a clear model for advancing the UK's digital adoption in energy infrastructure.

Singapore has overcome many of the barriers facing the UK. By embedding digital policy within national energy planning, coordinating institutional delivery, and securing foundational trust through cybersecurity and skills investment.

[332] OEUK (2023), 'Offshore Energy Data & Digital Maturity Survey 2023'
[333] IMD World Digital Competitiveness Ranking 2024

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