Energy Sector Digitalisation

Overview

- Energy sector digitalisation refers to the integration of digital technologies into systems such as generation plants, electricity networks and consumer meters.
- Artificial intelligence, the Internet-of-Things, distributed ledgers, and other technologies, could drive novel business models, incentivise economic growth and improve consumer experiences.
- Digital technologies will require greater access to data and combining of datasets collected by different energy stakeholders.
- Other challenges include protecting consumers' privacy and risk of cyberattacks.
- Certain initiatives have suggested possible approaches to improving data practices, enhancing cyber security resilience, and promoting innovation in the energy sector.

Digitalisation of the energy sector can support progress towards key UK objectives, such as decarbonisation to achieve Net Zero emissions targets. More broadly, digital technologies may also present both opportunities and challenges by transforming the way energy is generated, transmitted, regulated, and traded, as well as changing how consumers use energy.

Background

'Digitalisation' refers to the incorporation of digital technologies within a sector.[1,2] In the past decade, there has been increasing use of digital technologies in the energy sector, including the use of digital sensors in electricity networks for supply monitoring and the installation of smart meters for analysing consumers' demand.[1,3–6] The pace of energy sector digitalisation is increasing and projections by organisations such as the International Energy Agency suggest that this trend will continue over the next decade.[7–12] In 2021, the Government said that the UK can become a global leader in the development of tools for energy sector digitalisation.[13]

Digitalisation can help to support decarbonisation of the energy sector as the UK seeks to achieve Net Zero emissions by 2050, by enabling more widespread use of renewable energy sources.[14–17] Digital technologies can improve the flexibility and efficiency of energy systems by helping supply to better match demand.[18,19] The Department for Business, Energy and Industrial Strategy (BEIS) estimates that by 2050, improved system flexibility through digitalisation could reduce overall UK energy system costs by up to £10bn annually and create up to 24,000 jobs.[13,20] Digitalisation can help support energy systems decentralisation (where power generation uses small-scale assets closer to the consumption site), and enables different energy systems to be connected together (such as electricity transport, and renewables) leading to improved efficiency[21–24] as well as greater consumer choice and improved services.[25,26]

Digitalisation is featured prominently in the UK Government's 2020 Energy White Paper and 'using digital innovation to reach Net Zero' is one of ten technological priorities identified by the Department for Digital, Culture, Media & Sport (DCMS).[27,28] In July 2021, the Government published its first energy sector digitalisation strategy and action plan, which outlined ways to digitalise the energy sector through providing leadership, collaborating with the sector to develop digital tools, and ensuring regulation and policies incentivise digitalisation.[25]

Although digitalisation is progressing across the whole energy system, efforts have concentrated on the electricity sector, particularly as heat becomes electrified, electric vehicles are introduced, and fossil fuels are phased out and replaced by renewables and hydrogen (POSTnote 645). This POSTnote presents an overview of key digital technologies and how they are used in the energy sector. It also examines the potential benefits and challenges created by digitalisation.

Energy sector data

Digital technologies are underpinned by data, which give systems the information they need to carry out actions and operate with each other.[29] Work is ongoing across a wide range of sectors, including energy, to develop innovative techniques to analyse larger and more complex datasets (POSTnote 468).[30–34] In the energy sector, certain datasets, such as some types of consumer and supplier data, are subject to data privacy and governance controls:[35]

- **System data:** encompasses information about the infrastructure which is used to generate, transform, store, trade, transport or control energy.[30] Examples of system data include the location and condition of infrastructure (e.g. location of power stations and substations and whether they are operating), and the capacity and output of generation assets (e.g. megawatt output of an offshore wind farm).
- **Consumer and supplier data:** consists of data about customers and their energy use.[1] For example, data from smart meters about customers' energy usage patterns and information collected from customers such as their billing details. Some of this data may fall under the legal definition of 'personal data' (information that relates to an identified or identifiable individual) and is subject to data protection legislation. Access to smart meter data is governed by the Data Access and Privacy Framework.[36]

Digital technologies in the energy sector

Technologies such as the Internet-of-Things (IoT) and Artificial Intelligence (AI) , as well as Distributed Ledger Technology (DLT) (which is in earlier stages of being applied in the energy sector) have the potential to significantly change the way that the energy system operates (Box 1).[37–41] These technologies have a number of benefits, including the capability to make energy systems more connected, sustainable, and reliable. They can support improved analysis of energy sector data and can also allow deeper penetration of renewables.[42]

Internet of things

A 2019 report by research and advisory firm Gartner estimated that approximately 1.17 billion IoT devices were installed worldwide in utility grids.[43] The use of IoT devices is expected to increase in the energy sector.[44] A key benefit is that they can be incorporated into the electricity network to help create 'smart grids' that enable the monitoring of electricity flow and infrastructure.[42,45] IoT technology will also facilitate the integration of local, small scale energy generation units (such as rooftop solar panels) into the energy system.[46,47] Smart meters are a type of IoT device that measure household energy consumption and make the data available in real time to consumers and suppliers. As of March 2021, there were 24.2m smart meters in homes and small businesses in Great Britain, representing 44% of all meters.[48] Though IoT devices consume electricity, a 2021 report by technology research and development company InterDigital estimated that by 2030, IoT devices will help save around eight times the energy they consume via functions such as optimising consumption.[49–51]

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%.[52] UK companies including National Grid ESO, Western Power Distribution, and Octopus Energy are developing AI platforms and running pilot programmes.[53–55] AI is likely to play a key role in four domains:

- **Modelling and optimisation:** Creating virtual representations of energy infrastructure (such as power plants) and optimising their performance by incorporating weather forecasting information.[56,57]
- **Maintenance and security:** Optimising maintenance schedules of energy system assets; and improving both their cyber and physical security.[1]
- **Customer-facing services:** Enabling consumers to understand their usage patterns; and making suggestions (such as recommending a tariff based on consumption data).
- **Markets and investment:** Enabling automated energy trading between consumers who also produce energy.

Box 1: Disruptive digital technologies

Internet of things

The IoT refers to a network of interconnected devices capable of communicating directly with each other without the need to interact with humans (POSTnote 593).[58] It uses hardware and software to collect and process data and typically features:[59]

- **Sensors**, such as temperature and humidity sensors to collect data about users or the environment.
- **Actuators**, that respond to an input and can perform an action such as disengaging a switch.
- **Network connectivity**, to connect to the internet, typically via a wireless connection such as Wi-Fi.

Artificial intelligence

AI broadly refers to the ability of machines to perform tasks that traditionally required human intelligence. AI systems can identify patterns and trends in large datasets, and those outputs can be used to support human decision making. AI systems can be used to produce a prediction, a recommendation or a classification.[60–62] For example, an AI system may make a prediction that energy demand will be lower next Sunday morning. Particular progress has been made in 'machine learning', a type of AI (POSTnote 633).[63,64]

Distributed ledger technology

A distributed ledger is a digital records system that allows multiple identical copies of a record to be stored on different computers in a network.[65] The databases are updated and synchronised automatically each time new data are added. Multiple users are allowed to update the ledger, meaning that it can be controlled by a group of participants.[66,67] 'Blockchain' is a type of DLT characterised by the way that the data is structured within the ledger: new transactions that need to be recorded are grouped together into 'blocks' before being added onto the database[68–70] (POSTbrief 28).[71]

Distributed ledger technology

DLT has been proposed as way to manage future energy systems, which are likely to be increasingly decentralised.[66] DLT could be used to enable 'peer-to-peer' electricity trading between multiple different parties, including small-scale local energy producers, without central supervision.[72] It could be used to provide a reliable, decentralised way of registering network assets (such as overhead lines, underground cables, and substations).[73,74] Agreements outlining transaction terms can be implemented via 'smart contracts', which are digital contracts that are recorded on a distributed ledger.[75] In 2019, National Grid, UK Power Networks, and SP Energy Networks in collaboration with software developer Electron, launched the 'recorDER' project with the aim of developing a blockchain-enabled register of network assets accessible to key energy sector stakeholders.[76,77]

Using new technology in the energy sector

The technologies detailed above, either alone or in combination, can be used to develop innovative applications that make the energy sector more efficient, improve the capabilities of the energy system and lead to products and services that improve customer experiences.[25,51,78] As the energy sector is currently in a transitory phase where digitalisation is being progressively implemented, there is no consensus on the most important applications of digitalisation. Some applications that are being widely researched and trialled include the use of digital twin models, the concept of demand-side flexibility and the creation of innovative products and services such as time-of-use tariffs. These are explained below.

Digital twin models

A digital twin is a virtual replica of a real-life physical system. Digital twins use data collected from the real-life system (which is typically analysed using AI) to inform decisions about the operation of the physical system. In the energy sector, data collected by IoT devices and information about the design of energy infrastructure can be used to develop digital twin models. Examples include the modelling of power generation plants and network substations.[79,80] Before construction, digital twins can be used to replicate physical and operational aspects of a generation plant and aid in improving operations and maintenance.[81] In 2018, the Government launched the National Digital Twin Programme (NDTp).[82,83] As part of the NDTp, the Climate Resilience Demonstrator project was launched, which aims to improve infrastructure resilience to climate change by developing digital twins of energy and telecoms networks.[84]

Demand-side flexibility

A flexible energy system has the ability to shift in time (or location) the generation or consumption of energy (POSTnote 587).[13] To date, much of the system flexibility has been provided by the 'generation-side' of the system, by adjusting supply according to demand. However, digital technologies also enable 'demand-side' flexibility (or simply, demand flexibility) where consumption can be shifted towards periods when energy is cheaper and possibly coming from renewable sources.[85] For example, using a dishwasher during the day when renewable energy generation from solar panels is abundant.[86] AI is a key enabling technology for demand-side flexibility as it allows demand-side data to be processed efficiently and helps in predicting demand based on previous trends.[87] DLT has also been proposed by experts as a technology that can support demand flexibility through peer-to-peer energy trading.[88,89] In July 2021, the Government published its 'Smart Systems and Flexibility Plan' that presents a vision to improving flexibility in the energy system.[13]

Time-of-Use Tariffs

Time-of-Use (ToU) tariffs are a novel pricing plan for energy consumption, designed to incentivise flexible demand for energy by consumers.[90] A ToU tariff is a plan where the price of a unit of energy varies during a 24 hour period.[91] There are two main types of ToU tariffs; static and dynamic. With *static* ToU tariffs, the same prices are offered at the same times each day. With *dynamic* ToU tariffs, energy prices can vary continually and are calculated in real-time depending on various factors. For example, prices may be lower when wind generation is higher.[92,93] Consumers who are willing to shift their energy use or change their usage patterns could benefit from lower energy prices by setting a timeframe in which their appliances need to operate and allowing an automated system to choose the optimal time.[90] IoT devices that monitor energy consumption patterns and AI systems that can be used to dynamically calculate energy prices are key enabling technologies.

Challenges

The widespread adoption of digital technologies in the energy sector is associated with a number of technical, regulatory and policy challenges.

Technical challenges

Technical challenges include the limited availability of data, lack of data governance and interoperability, as well as the risk of cyberattacks on IT systems. There may also be future challenges that arise as more IoT devices are deployed, such as hardware obsolescence (electronic devices becoming obsolete due to innovation or changes in technology) leading to an increase in electronic waste.[94] Wider issues around electronic waste are discussed in the House of Commons Environmental Audit Committee's November 2020 report on Electronic Waste and the Circular Economy.[95]

Data Availability and use

Historically, use of data in the UK energy sector has been constrained by a number of factors:[30]

- **Fragmentation:** Data is often collected and held by multiple stakeholders, with limited sharing between them.[1,30]
- **Risk:** Given the criticality of the energy infrastructure and the cybersecurity risks associated with digitalisation, technological upgrades that promote greater use of data have been limited.[96,97]
- **Skilled workforce:** It can be challenging for organisations within the energy sector to recruit staff with the required engineering and data management skills.[98]
- **Established practices:** It has been difficult for innovative companies to challenge the established data practices in the energy sector.[30]

Data Governance and standards

Data governance encompasses the actors and actions within a sector or organisation that together shape how data is managed and used.[99] In the UK energy sector there are currently no overarching standards for the collection and recording of data. However, in May 2021 the British Standards Institution published two standards for integration and communication between energy sector IoT devices.[100,101] In addition, there is no central body that enforces data standards in the sector. This has led to a lack of data sharing between stakeholders, with datasets largely existing in siloes.[1,102]

Cyberattacks

Digital systems in the energy sector could be a target for a cyberattack (POSTnote 554).[103–105] Cyberattacks could affect the capability of the energy system to deliver a reliable service to consumers and can lead to cascading failures in other sectors, such as telecoms and water supply networks, which rely on the energy system to function.[106–108] Studies have estimated a daily cost of up to £111m if there was a cyberattack on the electricity distribution network that serves London and surrounding areas, and economic losses of £12-86bn for an attack on a UK regional distribution network.[108,109]

The energy industry uses 'energy control systems' to manage and control the generation, transmission and distribution of electricity.[110] Earlier energy control systems were not based on digital technology, or accessible remotely, therefore making the possibility of cyberattacks less likely.[111,112] Stakeholders have highlighted that greater deployment of digital technologies, including the use of digital control systems with increased internet connectivity, is likely to increase the risk of a cyberattack on the energy system.[113–116] There are also concerns that, as infrastructure becomes more distributed, it may be more difficult to manage threats centrally.[117,118] Actions that address these challenges are discussed later.

Impact on consumers

Allowing suppliers to access consumer data can enable them to offer users improved and personalised products and services.[119–121] Consumer data is also likely to play an increasing role in improving demand-side flexibility. However, there are privacy concerns around the collection and use of this kind of data. There are also challenges around AI systems making automated decisions about what products or services to offer consumers due to the risk of those systems perpetuating biases (POSTnote 633).[122–126] Concerns raised by consumers (via advisory organisations such as Citizens Advice) around how energy data is used, include:[127–129]

- **Extrapolation of sensitive information:** Depending upon the frequency that consumer energy data is collected, sensitive information about the user could be inferred.[119] Smart meter data recorded at half a second intervals can theoretically be used to identify when individual household appliances are being used.[130] When smart meter data is collected at 10 to 30 minute intervals, occupancy and activity patterns can be inferred. This could increase the risk of burglary if obtained by malicious actors.[131] Smart meter data recorded at 30 minute intervals can be obtained by Distribution Network Operators (DNOs), companies licensed to distribute electricity, if the data is aggregated and anonymised.[1]
- **Consent:** Though the bill-payer of a shared occupancy household may consent to sharing smart meter data, other household members may not consent, may be unaware that the data is being shared, or may not fully understand what they are consenting to and how to withdraw consent.[119,132]
- **Third-party data linking:** This refers to the process through which insights, such as personal information, can be inferred by linking consumer energy data with other data sources such as social media. A concern with third-party data linking is the potential to identify individual users. The lack of transparency around how insights may be drawn from linked data sources, and what sources might be used, makes it challenging for consumers to be fully informed about future uses and insights that could be inferred from their data.[119,133]

Regulatory and policy challenges

Many stakeholders have highlighted that one of the challenges in this area is that digital technologies tend to develop faster than the regulatory measures that govern them.[134] There is a growing consensus that the pace of technology development across all sectors is set to accelerate.[135]

Regulatory, policy and technical solutions

A number of measures could help to address some of the challenges outlined in the previous section.

Improving data practices

In June 2019, the Energy Data Taskforce (EDTF), a consortium established by BEIS, Ofgem, and Innovate UK, and run by Energy Systems Catapult, released its first report that addressed how data practices, including data access, could be improved across the UK energy sector to facilitate digitalisation.[30,136] Its recommendations included the industry-wide adoption of data and digitalisation strategies and the promotion of 'presumed open' data across the sector such that it is available to other organisations.[30] The 'Open Energy' project led by the non-profit Icebreaker One aims to deliver a platform that enables better sharing of energy data.[137–140]

Following these recommendations, Ofgem ran a consultation on draft Data Best Practice Guidance, which closed in June 2021.[141–144] In May 2021, BEIS, Ofgem and Innovate UK, launched the Energy Digitalisation Taskforce (EDiT) which, like the EDTF, is run by Energy Systems Catapult.[145] The EDiT is focused on the market design, digital architecture and governance of the UK energy system and will deliver a set of recommendations in 2022.[146] The recent Government energy sector digitalisation strategy (published in July 2021) plans to have standards and regulatory frameworks that govern energy data developed by the mid-2020s.[25]

Cyber security

A number of pieces of guidance have been produced to improve the cyber security of energy sector infrastructure. The 2019 National Cyber Security Centre (NCSC) third Cyber Assessment Framework (CAF) provides organisations that operate within critical national infrastructure sectors with guidelines for assessing their cyber resilience.[147] Recognising the need for tailored cybersecurity guidelines for Distributed Energy Resources (DERs) (e.g. rooftop solar panels), the Energy Networks Association produced a guidance document in 2020 to improve the cybersecurity of DERs in the UK.[148,149] In 2020, Ofgem published a set of cyber resilience guidelines for gas and electricity network companies and their stakeholders, which aims to support security professionals within network companies to improve the resilience of their IT systems.[150,151]

Innovation trials

A regulatory sandbox is a framework that allows innovative products, services and business models to be trialled in a real-world environment without needing to comply with certain regulatory requirements.[152,153] In the UK energy sector, the implementation of regulatory sandboxes is relatively new, with Ofgem launching its first initiative in December 2016.[154,155] In July 2020, Ofgem's new Energy Regulation Sandbox was launched with licences being granted in May 2021.[156–158]

POST is an office of both Houses of Parliament, charged with providing independent and balanced analysis of policy issues that have a basis in science and technology. POST is grateful to Rodosthenis Charalampous for researching this briefing, to UKRI for funding his parliamentary fellowship, and to all contributors and reviewers. For further information on this subject, please contact the co-author, Dr Lorna Christie.

Endnotes

1. Rhodes, A. (2020). Digitalisation of Energy: An Energy Futures Lab Briefing Paper. Energy Futures Lab.
2. Bloomberg, J. Digitization, Digitalization, And Digital Transformation: Confuse Them At Your Peril. *Forbes*.
3. BEIS Smart Meter Policy Framework Post 2020: Minimum Annual Targets and Reporting Thresholds for Energy Suppliers.
4. Parliamentary Office of Science and Technology (2014). Smart Metering of Energy and Water - POSTnote 471.
5. Weigel, P. *et al.* (2019). Review and Categorization of Digital Applications in the Energy Sector. *Applied Sciences*, Vol 9, 5350. Multidisciplinary Digital Publishing Institute.
6. BEIS (2021). UK Innovation Strategy: leading the future by creating it. *GOV.UK*.
7. Verma, D. P. *et al.* (2020). Digitalization: enabling the new phase of energy efficiency. *Group of Experts on Energy Efficiency seventh session*,
8. UN Digitalization and the future of Energy Systems. United Nations.
9. EC-MAP (2018). New Policy for an era of Energy Digitalization.
10. BEIS (2020). Government sets out plans to drive up smart meter installations. *GOV.UK*.
11. OECD (2019). Data in the Digital Age. Vol 274,
12. International Finance Corporation (2020). Artificial Intelligence in the Power Sector. 8.
13. BEIS (2021). Transitioning to a net zero energy system: Smart Systems and Flexibility Plan 2021. 89.
14. Şerban, A. C. *et al.* (2020). Artificial Intelligence for Smart Renewable Energy Sector in Europe—Smart Energy Infrastructures for Next Generation Smart Cities. *IEEE Access*, Vol 8, 77364–77377.
15. IEA Net Zero by 2050 - A Roadmap for the Global Energy Sector.
16. Ofgem (2021). *Review of GB energy system operation*.
17. The Royal Society (2020). Digital technology and the planet: harnessing computing to achieve net zero.
18. Ofgem Electricity system flexibility. *Ofgem*.
19. Miller, J. *et al.* (2021). Flexible Electricity Systems. POST.
20. BEIS (2019). Energy Innovation Needs Assessments. *GOV.UK*.
21. Brisbois, M. C. (2020). Decentralised energy, decentralised accountability? Lessons on how to govern decentralised electricity transitions from multi-level natural resource governance. *Global Transitions*, Vol 2, 16–25.
22. Tagliapietra, S. *et al.* (2019). The European union energy transition: Key priorities for the next five years. *Energy Policy*, Vol 132, 950–954.
23. IRENA (2018). Global Energy Transformation: A Roadmap to 2050. 76.
24. Sovacool, B. K. *et al.* (2019). Smart home technologies in Europe: a critical review of concepts, benefits, risks and policies. *Renewable & Sustainable Energy Reviews*, Vol 120, a109663. Elsevier.
25. BEIS (2021). Digitalising our energy system for net zero: strategy and action plan 2021. 44.
26. Britton, J. *et al.* (2021). Exploring the potential of heat as a service in decarbonization: Evidence needs and research gaps. *Energy Sources, Part B: Economics, Planning, and Policy*, Vol 0, 1–17. Taylor & Francis.
27. BEIS (2020). Energy White Paper: Powering our Net Zero Future. 170. UK Government.
28. DCMS Our Ten Tech Priorities.
29. UKCS (2020). UKCS Data & Digital Maturity Survey.
30. Energy Systems Catapult (2019). A Strategy for a Modern Digitalised Energy System.
31. POST (2014). Big Data Overview.
32. BEIS (2017). Digital, Data & Technology (DDaT) Strategy.
33. Apogaeis How Big Data is adding a Bigger Advantage in the Energy and Power Sector.
34. Bhattarai, B. P. *et al.* (2019). Big data analytics in smart grids: state-of-the-art, challenges, opportunities, and future directions. *IET Smart Grid*, Vol 2, 141–154. IET Digital Library.
35. Energy Systems Catapult (2018). Energy Data Review.
36. BEIS (2018). Smart Metering Implementation Programme: Review of the Data Access and Privacy Framework.
37. IEA (2017). *Digitalization and Energy*. 188.
38. Deloitte (2017). Connected Customers - The transformation imperative for Utilities in a digitally disrupted world. Deloitte.
39. Sherule, A. J. *et al.* (2021). Disruptive technologies in energy and environment. in *2021 International Conference on Computational Intelligence and Knowledge Economy (ICCIKE)*. 37–41.
40. Ahmad, T. *et al.* (2021). Artificial intelligence in sustainable energy industry: Status Quo, challenges and opportunities. *Journal of Cleaner Production*, Vol 289, 125834.
41. Brilliantova, V. *et al.* (2019). Blockchain and the future of energy. *Technology in Society*, Vol 57, 38–45.
42. Santos, D. *et al.* (2019). IoT Power Monitoring System for Smart Environments. *Sustainability*, Vol 11, 5355. Multidisciplinary Digital Publishing Institute.
43. Gartner (2019). Gartner Says 5.8 Billion Enterprise and Automotive IoT Endpoints Will Be in Use in 2020. *Gartner*.
44. Statista (2016). Number of IoT devices 2015-2025. *Statista*.
45. Ghasempour, A. (2019). Internet of Things in Smart Grid: Architecture, Applications, Services, Key Technologies, and Challenges. *Inventions*, Vol 4, 22. Multidisciplinary Digital Publishing Institute.
46. IRENA (2019). Internet of Things – Innovation landscape brief.
47. Intel Energy IoT - Transforming Smart Energy Grid. *Intel*.
48. BEIS (2021). Smart Meter Statistics in Great Britain: Quarterly Report to end March 2021.
49. Strathern, F. (2021). IoT technology will save eight times the energy it consumes by 2030, new report shows. *Internet of Things News*.
50. 6Gworld Sustainability in New and Emerging Technologies. *6GWorld*.
51. Hossein Motlagh, N. *et al.* (2020). Internet of Things (IoT) and the Energy Sector. *Energies*, Vol 13, 494. Multidisciplinary Digital Publishing Institute.
52. PwC *et al.* (2020). How AI can enable a Sustainable Future.
53. TechUK (2021). AI for Energy.
54. Octopus Energy (2020). Octopus Energy Group boosts Kraken's capabilities with innovative 'EnTech' software. *Octopus Energy*.
55. Western Power Distribution (2015). Adaptation to Climate Change Second Round Report.
56. Vogel, L. *et al.* Artificial Intelligence for the Integrated Energy Transition.
57. BEIS *et al.* (2018). Office for Artificial Intelligence. *GOV.UK*.
58. Sutherland, N. *et al.* (2021). Regulating the Internet of Things.
59. Čolaković, A. *et al.* (2018). Internet of Things (IoT): A review of enabling technologies, challenges, and open research issues. *Computer Networks*, Vol 144, 17–39.
60. Information Commissioner's Office (2019). Explaining decisions made with AI.
61. Royal Society (2017). Machine learning: the power and promise of computers that learn by example.
62. Sarker, I. H. (2021). Machine Learning: Algorithms, Real-World Applications and Research Directions. *SN COMPUT. SCI.*, Vol 2, 160.

63. Government Office for Science (2016). Artificial intelligence: opportunities and implications for the future of decision making.
64. Hammond, K. (2017). The Periodic Table Of AI.
65. Botticelli, M. *et al.* (2020). Challenges and opportunities of Blockchain technology in the energy sector. in 1–6.
66. POST POSTbrief 28.
67. NCSC (2021). Distributed ledger technology.
68. Benos, E. *et al.* (2019). The Economics of Distributed Ledger Technology for Securities Settlement. *ledger*, Vol 4,
69. Dannen, C. (2017). Introducing Ethereum and Solidity: Foundations of Cryptocurrency and Blockchain Programming for Beginners. Apress.
70. Parjuangan, S. *et al.* (2020). Systematic Literature Review of Blockchain based Smart Contracts Platforms. in *2020 International Conference on Information Technology Systems and Innovation (ICITSI)*. 381–386.
71. Government Office for Science (2016). *Distributed Ledger Technology: beyond block chain*. 88.
72. PwC (2016). Blockchain - an opportunity for energy producers and consumers?
73. Electron Electron - Empowering Distributed Energy Markets. *Electron*.
74. National Grid Working near our assets. *Electricity Assets*.
75. Iberdrola (2020). How can blockchain be used to certify the source of green energy? *Iberdrola*.
76. UK Power Networks (2019). UK Power Networks - recorDER. *UK Power Networks*.
77. Electron (2019). Project RecorDER. *Electron*.
78. Andoni, M. *et al.* (2019). Blockchain technology in the energy sector: A systematic review of challenges and opportunities. *Renewable and Sustainable Energy Reviews*, Vol 100, 143–174.
79. Kong, C. W. (Leo) *et al.* (2021). Interactive Digital Twins Framework for Asset Management Through Internet. in *2020 IEEE Global Conference on Artificial Intelligence and Internet of Things (GCAIoT)*. 9345890. IEEE.
80. Walters, A.-M. (2019). *How Digital Twins Will Drive Innovation in the Energy Sector*. 5.
81. GE Power Digital Solutions (2016). GE Digital Twin.
82. Centre for Digital Built Britain (2019). National Digital Twin Programme.
83. National Infrastructure Commission Data for the public good. 76.
84. Digital Twin Hub Climate Resilience Demosntrator (CReDo). *DT Hub Community*.
85. Parrish, B. *et al.* (2020). A systematic review of motivations, enablers and barriers for consumer engagement with residential demand response. *Energy Policy*, Vol 138, 111221.
86. IRENA (2019). Time-of-use tariffs – Innovation Landscape Brief. 18.
87. IRENA (2019). Demand-side flexibility for power sector transformation.
88. Ellis, P. *et al.* (2018). Flexibility Trading Platform—Using Blockchain to Create the Most Efficient Demand-side Response Trading Market. in *Transforming Climate Finance and Green Investment with Blockchains*. (ed. Marke, A.) 99–109. Academic Press.
89. Pop, C. *et al.* (2018). Blockchain Based Decentralized Management of Demand Response Programs in Smart Energy Grids. *Sensors*, Vol 18, 162. Multidisciplinary Digital Publishing Institute.
90. Citizens' Advice (2020). The value of time of use tarrifs.
91. Riley, G. (2021). Time of Use Tariffs: Saving the UK Grid?
92. Smart Meters Time-of-use tariffs: the benefits.
93. Smart Energy GB (2020). Time-of-use tariffs: the benefits.
94. Sovacool, B. K. *et al.* (2020). Imagining sustainable energy and mobility transitions: Valence, temporality, and radicalism in 38 visions of a low-carbon future. *Soc Stud Sci*, Vol 50, 642–679. SAGE Publications Ltd.
95. House of Commons Environmental Audit Committee (2020). Electronic Waste and the Circular Economy.
96. ARUP (2021). How do our analogue energy systems become data-powered innovators.
97. Cabinet Office (2017). Public Summary of Sector Security and Resilience Plans.
98. UKCES (2015). Sector insights: skills and performance challenges in the energy sector.
99. The Royal Society (2020). The UK data governance landscape.
100. BSI (2021). PAS 1878 Energy smart appliances – System functionality and architecture.
101. BSI (2021). PAS 1879 Energy smart appliances – Demand side response operation.
102. USGS Data Standards.
103. McKinsey & Company (2019). Cybersecurity in a Digital Era.pdf.
104. Hielscher, S. *et al.* (2018). Contested smart and low-carbon energy futures: Media discourses of smart meters in the United Kingdom. *Journal of Cleaner Production*, Vol 195,
105. Livingston, S. *et al.* Managing cyber risk in the electric power sector. *Deloitte Insights*.
106. Dagoumas, A. (2019). Assessing the Impact of Cybersecurity Attacks on Power Systems. *Energies*, Vol 12, 725. Multidisciplinary Digital Publishing Institute.
107. Venkatachary, S. *et al.* (2017). Economic Impacts of Cyber Security in Energy Sector: A Review. *International Journal of Energy Economics and Policy*, Vol 7, 250–262.
108. Oughton, E. J. *et al.* (2019). Stochastic Counterfactual Risk Analysis for the Vulnerability Assessment of Cyber-Physical Attacks on Electricity Distribution Infrastructure Networks. *Risk Analysis*, Vol 39, 2012–2031.
109. Cambridge Centre for Risk Studies (2016). Integrated Infrastructure: Cyber Resiliency in Society.
110. U.S. Department of Energy (2006). Roadmap to Secure Control Systems in the Energy Sector. 58.
111. European Parliamentary Research Service Cybersecurity of critical energy infrastructure.
112. EECSP (2017). Cyber Security in the Energy Sector. European Commission.
113. World Energy Council Cyber challenges to the energy transition.
114. IEA (2020). Power systems in transition: Challenges and opportunities ahead for electricity security. OECD.
115. Desarnaud, G. (2017). Cyber Attacks and Energy Infrastructures: Anticipating Risks.
116. McKinsey & Company (2019). Perspectives on transforming cybersecurity.
117. McKinsey & Company (2020). The energy sector threat: How to address cybersecurity vulnerabilities.
118. IET (2017). Evidence from the Institution of Engineering and Technology to the Cyber Security: UK National Security in a Digital World inquiry.
119. Véliz, C. *et al.* (2018). Protecting data privacy is key to a smart energy future. *Nat Energy*, Vol 3, 702–704. Nature Publishing Group.
120. Accenture (2019). Serving small and medium-size businesses - Shaping customer experience their way.
121. Citizens' Advice (2019). Clear and in control - Energy consumers' views on data sharing and smart devices.
122. UK Data Service (2016). Legal and ethical challenges surrounding big data: energy data.
123. Morris, M. *et al.* (2020). Working Paper 2: Digital energy platforms. EnergyRev.
124. Carmichael, R. *et al.* (2018). Unlocking the potential of residential electricity consumer engagement with Demand Response - An Energy Futures Lab Briefing Paper.

125. Seoane, C. Why utilities adopting AI should put ethics first. *Atos*.
126. IRENA (2019). Artificial Intelligence and Big Data – Innovation Landscape Brief.
127. Citizens' Advice (2020). Summary report on energy suppliers' communication with consumers regarding smart meter data.
128. Citizens' Advice (2018). Contracts - Raising awareness of different consumer contracts and what you should know before signing up.
129. European Comission (2016). Study on Consumers' Attitudes Towards Terms Conditions (T&Cs). Social Science Research Network.
130. Carrie Armel, K. *et al.* (2013). Is disaggregation the holy grail of energy efficiency? The case of electricity. *Energy Policy*, Vol 52, 213–234.
131. Razavi, R. *et al.* (2019). Occupancy detection of residential buildings using smart meter data: A large-scale study. *Energy and Buildings*, Vol 183, 195–208.
132. Armoogum, S. *et al.* (2019). Privacy of energy consumption data of a household in a smart grid. in *Smart Power Distribution Systems*. (eds. Yang, Q. et al.) 163–177. Academic Press.
133. Webborn, E. *et al.* (2019). Utilising smart meter data for research and innovation in the UK. *Buildings: technologies and systems*,
134. OECD (2019). Regulatory effectiveness in the era of digitalisation.
135. (2021). Innovative and Agile Contracting for Digital Transformation and Industry 4.0: IGI Global.
136. Modernising Energy Data. *GOV.UK*.
137. Mission:data (2019). Energy Data Portability.
138. Information Commissioner's Office (2021). Right to data portability. ICO.
139. OECD (2021). Data portability, interoperability and competition.
140. Energy Systems Catapult Introduction to Interoperability in Energy Sector.
141. HM Government Modernising Energy Data. *GOV.UK*.
142. Ofgem An early draft of Data Best Practice guidance is available. *Ofgem*.
143. Energy Systems Catapult (2019). Have your say on Energy Data Best Practice. *Energy Systems Catapult*.
144. Ofgem (2021). Data Best Practice Guidance.
145. Energy Systems Catapult (2021). Energy Digitalisation Taskforce launches. *Energy Systems Catapult*.
146. Energy Systems Catapult (2021). Energy Digitalisation Taskforce. *Energy Systems Catapult*.
147. NCSC (2019). Cyber Assessment Framework.
148. Energy Network Association *et al.* (2020). Distributed Energy Resources – Cyber Security Connection Guidance.
149. Aseka, D. (2020). Energy Networks Association launches new cyber security guidance with BEIS and NCSC. *Current*.
150. Ofgem (2020). RIIO-2 Cyber Resilience Guidelines.
151. Ofgem Network price controls 2021-2028 (RIIO-2) - Electricity distribution price control 2023-2028 (RIIO-ED2). *Ofgem*.
152. Ofgem (2018). What is a regulatory sandbox?
153. Ofgem (2021). Sandbox Consent to not comply with Standard Licence Condition (SLC) 13.1(b) of the Electricity Distribution Licence.
154. Schittekatte, T. (2020). Regulatory sandboxes in the energy sector - the what, the who and the how. *Florence School of Regulation*.
155. Ofgem (2016). Innovation Link. *Ofgem*.
156. Barnes, N. (2020). Ofgem launches new, enhanced Energy Regulation Sandbox service. *Ofgem*.
157. Lempriere, M. (2021). Emergent Energy's microgrid solution awarded Energy Regulation Sandbox by Ofgem. *Current*.
158. Ofgem (2021). Regulatory Sandbox Repository. *Ofgem*.