UK Parliament POST

POSTNOTE

Number 677 September 2022

Energy Consumption of ICT

This POSTnote gives an overview of the energy use of Information and Communication Technology (ICT), including data centres, communication networks and user devices. It looks at forecasts for future ICT energy use, and how these may be impacted by trends in energy efficiency and emerging applications of ICT. It discusses monitoring and regulation of ICT energy use and associated challenges.

Overview

- The ICT sector used an estimated 4-6% of all electricity generated globally in 2020.
- Over the past decade energy efficiency across the ICT sector has improved, but demand for ICT has increased. This has resulted in overall energy use remaining mostly flat according to some estimates.
- Experts predict that ICT energy use is likely to increase to 2030. However, there is significant uncertainty in forecasts, which depend on trends in energy efficiency and applications of ICT such as crypto-mining.
- Some stakeholders say that more reporting and regulation of energy use is required to ensure the sector achieves climate targets.

Background

Using digital innovation to reach net zero is one of 10 'Tech Priorities' identified by the Department for Digital, Culture, Media & Sport.[1,2] Although digital technologies can reduce and optimise energy use across sectors (including the energy sector, POSTnote 655),[3] ICT infrastructure and devices themselves use a considerable amount of energy (mostly electricity). Data centres, communication networks and user devices accounted for an estimated 4-6% of global electricity use in 2020 (5-8% including televisions).[4–6] While predictions vary significantly, experts generally forecast that global ICT energy use is likely to increase over the next 5-10 years.[5–8]

Energy is used in the ICT sector to power user devices (such as laptops and smartphones), and the underpinning infrastructure, including communication networks and data centres. Estimates suggest that user devices consume more energy than networks and data centres combined,[4,5,8,9] with one study attributing 60% of use-phase electricity consumption of the ICT sector to devices (excluding TVs).[6] In the last decade there has been a significant increase in internet traffic and in the amount of data processed and stored in data centres.[10–12] Energy efficiency of ICT equipment has also increased rapidly, due to developments in computer devices and trends such as cloud computing (POSTnote 629).[5,7,10,13–15] Some experts say that efficiency improvements have enabled ICT energy use to remain relatively flat in recent years.[10,14] Others have suggested that efficiency improvements can increase demand for ICT and that efficiency improvements alone will not lead to a fall in energy use.[16,8,17,18]

Because the ICT sector is highly electrified, the carbon footprint associated with ICT energy use depends strongly on the global electricity mix. Some estimates suggest that ICT (including TVs) constitutes 2-3% of greenhouse gas (GHG) emissions globally (1.0-1.7 $GtCO_2e$).[4,8,9] The ICT sector is increasingly powered by renewable electricity sources.[10,19] Experts have said that more work is needed to decarbonise the electrical grid and ICT supply chains to ensure the sector reaches climate targets.[6,8,10]

This POSTnote summarises estimates of the energy used across the ICT sector and trends that may affect it. It discusses developments in energy efficiency and issues related to energy reporting and standards.

Energy use in the ICT sector

Research on energy use

There is limited evidence on the energy use of ICT, and a significant degree of uncertainty in existing estimates. There have been no academic studies that estimate energy use of the ICT sector in the UK.[20] Some studies look at individual aspects of ICT, regionally or globally, for example data centres or communication networks.[10,14,21–25] A few studies estimate global energy use of the whole ICT sector.[4,5,9] The methods and data sources used by studies varies, and differences in key assumptions and approaches can result in significant differences in the results. Additionally, the rapid pace of development in the ICT sector can mean estimates quickly become unrepresentative.[8,14]

This POSTnote focuses on direct operational energy, which refers to the energy consumed by equipment while in use. Embodied energy (Box 1) also contributes to ICT's energy use.

The overall effect of ICT on energy consumption is complicated by its indirect effects on other sectors, both energy savings as well as induced and rebound effects that increase energy use. For example, smart sensors are projected to enable significant energy efficiency savings in the energy sector (POSTnote 655).[3] Experts suggest that technologies should be evaluated for their net energy impacts across sectors as well as their direct energy use.[26–29]

Box 1: Operational and embodied energy use
Energy use is divided into two categories:

- **Operational** energy refers to the energy consumed while a device or piece of network infrastructure is in use.
- **Embodied** energy refers to the non-operational energy consumption such as the energy required for equipment manufacture, assembly, and disposal.

Operational energy is typically stated in terms of electricity use (TWh), whereas the embodied contribution tends to be reported in terms of carbon emissions ($MtCO_2e$). Embodied emissions are estimated to make up around 20%-30% of the ICT sector's total carbon emissions.[8] For user devices, the embodied emissions account for a larger proportion of overall carbon, estimated at around 50%.[8] This is partly due to the comparatively short lifetimes of user hardware.[30,31]

Data centre energy use
Data centres house servers and other ICT equipment. They store and process data, enabling services across the private and public sectors. Data centre energy use is determined by the energy needed for the ICT equipment and for the building in which the equipment is housed, which is typically dominated by cooling.[32,33] Generally, larger data centres operate more efficiently than smaller ones, in part because servers can use the same purpose-built cooling systems.[32,34] Very large 'hyperscale' data centres (containing over 5000 servers) can achieve very high efficiencies.[14,35] Data centre services are increasingly distributed via the cloud (POSTnote 629) which allows workloads to be better shared between servers and thereby reduce idle time of ICT equipment (Box 2).[15,10,32,36]

The International Energy Agency (IEA) report that global data centre energy use in 2020 was 200-250 TWh (equivalent to about 1% of global electricity demand), excluding crypto-mining.[10] A study by Swedish telecoms companies Ericsson and Telia forecast the carbon footprint of data centres to be 127 $MtCO_2e$ in 2020 (corresponding to about 212 TWh).[4,8,37] A few studies have estimated higher global energy use, with one estimating 400 TWh in 2018.[21] In 2020, trade association techUK reported that UK co-location data centres (sites serving many customers, hosted by a third party) consumed 0.8% of total UK electricity use.[38] Forecasts for future energy use are very uncertain due to the number of possible factors that could influence trends, but one estimate by the International Telecommunication Union (ITU) forecast that global data centre energy use would increase from about 230 TWh in 2020 to about 270 TWh in 2030.[6]

Box 2: Fixed and variable energy use
Some ICT equipment consumes energy when on, even if it is not being used. For example, home networking equipment such as modems and routers are continually powered even when no data transfer activities are taking place.[4,9,39] The proportion of energy use that is independent of data traffic/processing is known as the 'fixed' component (as opposed to the 'variable' component). Fixed energy use can be a significant fraction of overall operational energy, particularly for network operations.[9,22]

Communication networks energy use
Communication networks transfer data between homes and businesses and the internet, and for telephone, radio and TV services. Data are transferred via wired networks and mobile networks.[40] Wired networks tend to use less energy than mobile networks to transmit the same amount of data.[10] The operational energy used by networks is mostly fixed energy (Box 2).[9,22] Networks are built to allow for peak data traffic, which commonly is much higher than typical traffic, therefore much of the equipment is idle for most of the day.[9,22,41,42]

The global energy use of communication networks has been reported to be around 260-340 TWh in 2020[10] (around 1-1.5% of global electricity demand).[43] The study by Ericsson and Telia forecast the carbon footprint of networks to be 168 $MtCO_2e$ in 2020 (corresponding to about 280 TWh).[4,8,37] BT reported that its UK electricity use in 2021 was 2.3 TWh (around 0.8% of UK electricity demand).[25] The ITU study projected that networks' electricity use (wired and mobile) will remain relatively stable, from about 260 TWh in 2020 to about 270 TWh to 2030.[6]

User devices energy use
User devices refer to consumer electronics used in homes and businesses (such as laptops, smartphones and wearables). Studies differ in whether they include TVs in the ICT sector, resulting in differences in figures for energy use of devices.[4,8] Devices consume energy in their processors, storage drives, power supply units and displays. Energy use varies between devices, but smaller devices tend to use less energy.[4] Screen technology for TVs and monitors has improved in recent years, enabling significant energy savings.[44] User devices make up the largest proportion of energy use in the ICT sector when compared to data centres and communication networks.[4,5,45] ITU projected the global operational electricity use of devices (excluding TVs) to increase from 335 TWh in 2020 (equivalent to about 1.2% of global electricity use)[43] to 450 TWh in 2030.[6]

Improvements in energy efficiency of ICT
Energy efficiency and energy use
Energy use of ICT is difficult to predict, due to the uncertain impact of emerging trends (Box 3) and the rapid evolution of energy efficiency of ICT. Industry-led R&D efforts have improved the efficiency of devices and ICT infrastructure significantly over recent decades.[46,47] Efforts are motivated both by consumer expectations for size and battery life of devices and industry stakeholders' aims to reduce their energy costs.

Some stakeholders note that improvements in energy efficiency have kept the ICT sector's energy use from increasing significantly over the past decade despite increased demand.[10,14] However, other experts say that efficiency gains are a driver for the increased demand for ICT services, due to associated improvements in the capability of technology and reductions in cost.[8,48,49] They have expressed concerns that efforts to improve energy efficiency alone may not be sufficient to reduce overall energy use of the ICT sector.[8]

This section discusses technical strategies to improve the energy efficiency of ICT. Non-technical approaches such as regulations are discussed in the following section.

Improvements in electronic performance

Improvements in the energy efficiency of ICT equipment have mainly been enabled through increases in the number of transistors that can fit onto a silicon computer chip.[50] This trend cannot continue indefinitely because the distances between transistors will reach physical limits.[50] Some experts argue that the trend has already been slowing down.[51–54] Novel materials and architectures (such as quantum computing, POSTnote 552)[55] may enable efficiency improvements to continue, but many are not expected to be ready for use until 2030 or later.[56]

Specialised silicon computer chips have been developed for particular applications, such as for videogames and cryptocurrencies.[57,58] Research suggests that energy can be used more efficiently when software designers develop applications to best use the computer hardware that they will run on.[59] These ideas are being developed as part of growing industry interest in sustainable software design.[60–64]

Data centre heat management

A significant operational energy requirement of data centres is for cooling.[65] This is typically achieved via air conditioning.[33,65] Consolidating smaller data centres into larger ones leads to lower overall energy use, as servers can use the same purpose-built cooling systems.[14] Some experts have highlighted that there is scope for individual small data centres to improve their cooling infrastructure.[66,67] Large data centres can sometimes be located in cooler climates to reduce energy needed for cooling.[68] Cooling efficiency can also be improved by using machine learning,[69] and liquid-submerged servers.[70,71]

Waste heat generated by data centres can be captured and used to heat buildings. For example, in Sweden, heat from data centres is directed into a district heat network (POSTnote 632).[72–74] Heat-reuse systems must be considered at the build stage of a data centre, as retrofitting can cause service disruptions.[71] techUK has said that barriers to reusing data centre heat include the heat's low quality (i.e. its relatively low temperature) and that the Government's Industrial Heat Reuse Support policy is not well suited to data centres.[71]

Modernisation of communication networks

Technology upgrades can offer improved energy efficiency in the communication network. Currently, UK wired access networks (POSTbrief 24) mostly use copper or a mix of fibre-optic and copper cables.[75] Fibre-optic networks are more energy efficient than copper, as they allow for a greater amount of data to be transmitted per unit of energy used.[76–79] The UK Government has set a target of full-fibre broadband in 25 million homes by 2026 (CBP 8392).[40,41]

Box 3. Impacts of emerging trends

Several emerging trends are thought to have the potential to impact the energy use of ICT. Examples include:

- **Blockchain:** blockchain technology (POSTbrief 28) enables the transaction of digital assets such as cryptocurrencies and non-fungible tokens.[80] One estimate found that Bitcoin used around 110 TWh of electricity in 2021, equivalent to roughly half the estimated energy used by all (non-crypto) data centres globally.[81,10] The dominant mechanism for recording transactions (via crypto-mining) is energy-intensive (POSTbrief 28).[80,82–85] Less energy-intensive mechanisms have been developed but have not been widely implemented.[84,86,87]
- **The Internet-of-Things (IoT):** One estimate suggests that the number of IoT devices (POSTnote 593),[88] will increase almost 3-fold from 2020 to 2025.[89] Some groups suggest that the application of IoT will result in overall energy savings, whereas others have noted IoT's significant embodied energy requirements.[90–92]
- **Machine Learning (ML):** the use of ML (POSTnote 633)[93] is expected to increase across sectors.[94] Energy is needed for ML development and in its application.[95–97] The increasing size of the models has led to calls for developers to document and reduce their energy use.[95,29]

The effect of 5G mobile networks (POSTbrief 32)[98] on the energy use of communication networks is contested. Some studies suggest that 5G networks have a better operational efficiency than older networks like 3G and 4G.[99–102] However, some of the higher frequency radio waves likely to be used in future 5G networks will require more densely positioned masts and hence more active network equipment overall.[103] 5G is generally expected to lead to an initial increase in overall energy use of networks.[99,104] However, there are few studies in this area, and the full range of indirect effects of 5G are uncertain.[101,102] Shutting down old networks is expected to improve overall energy efficiency of mobile networks.[10] The UK Government plans to decommission 2G and 3G by 2033.[105,106]

Power management techniques

Many devices do not need to be powered continuously and energy savings can be made by using low-power modes or turning the device off. User devices have already seen significant progress in this area, with energy saving techniques now built into laptops and PCs.[51,107] The high fixed energy component of communication networks (Box 2) has motivated improvements in power management for network devices. For example, 5G networks are being designed to limit the number of signals transmitted during low data traffic periods, allowing parts of the networks to be switched off.[108,109]

Edge computing

Edge computing (POSTnote 631)[110] involves the use of computing resources (including data storage and processing) located close to the devices which require them. This reduces the amount of data that needs transferring over the internet.[111] However, performing tasks in edge computers that would otherwise be performed in hyperscale data centres may have associated reductions in energy efficiency, as the advantages of consolidation are lost.[112] There is not currently a consensus on how edge computing will affect overall energy use of ICT.[112–115]

Regulation, standards and monitoring

Data collection and reporting

Many stakeholders highlight the lack of good quality, reliable data on the energy use of ICT.[7,10,14,26,116] There is no requirement for companies in the UK to report specifically on their ICT energy use or emissions. However, this may be captured as part of broader reporting mechanisms:

- Energy Savings Opportunity Scheme (ESOS) – large companies must evaluate their total energy consumption every four years and confirm compliance to the Environment Agency (but not report the figures).[117]
- Streamlined Energy and Carbon Reporting (SECR) – large companies must report their electricity use and GHG emissions in annual reporting to Companies House. Established in 2019, reporting in 2020 has been delayed by the pandemic. Few companies have filed reports so far.[118]

These policies do not apply to the public sector or small and medium sized enterprises (SMEs), but voluntary contributions are encouraged.[118] Under the Greening Government Commitments framework, Government departments are required to report annually on emissions specifically relating to ICT use.[119,120] techUK has suggested that excluding SMEs and the broader public sector from energy use reporting requirements creates an unbalanced view of data centre energy use, particularly as some evidence has shown that the energy efficiency of public sector data centres is substantially worse than average.[36,71,121]

Energy use of small data centres can be difficult to track and disaggregate from the rest of the company's energy use.[116] Some hyperscale and larger co-location data centre operators consider ICT energy use figures to be sensitive proprietary information, although most do publicly disclose energy use and emissions for the company overall.[14,122–128] Some experts have suggested that an independent organisation could be set up to collect and publish average figures from across the sector.[14]

It can be particularly difficult to attribute energy use for digital services (such as media streaming), as they use many parts of the ICT network.[129,9,130] Some providers have partnered with academics to estimate their energy use and emissions.[39,131,132]

Decarbonisation of energy

ICT companies are a major buyer of renewable energy, typically through Power Purchase Agreements.[71,133] ICT operational emissions, including those from user devices, could be reduced further by decarbonising the electrical grid. The UK Government plans to decarbonise the electrical grid by 2035.[1,134] The ITU has projected that, assuming the electrical grid decarbonises at a sufficient rate, emissions from ICT could reduce by 50% from 2020 to 2030.[6] However, the ITU report notes that the rate of decarbonisation assumed is very challenging.[6] Some UK-based experts say that current ICT climate targets are not sufficient to keep ICT emissions in line with the Paris Agreement.[8]

Regulation, standards and industry initiatives

Various UK and international regulations and standards apply to the ICT sector or segments of it (Box 4). Although standards are voluntary, reported compliance is high.[135] However, some experts suggest that voluntary initiatives are insufficient and new compliance mechanisms are required to enforce them.[8,116]

In the UK, companies can sign up to the Climate Change Agreement (CCA) with the Environment Agency.[136] For data centres, the CCA gives a discount on the Climate Change Levy conditional on certain energy efficiency targets being met.[137,138] In the last reporting period, of the 129 data centre sites signed up to the scheme, 29% failed to meet the targets set, and were required to pay a non-compliance fee.[139]

Many ICT companies have committed to significant reductions in emissions.[140] Standards for target setting are defined through the Science Based Targets initiative and Greenhouse Gas Protocol.[141,142] Some companies have faced criticism for their net-zero plans not being sufficiently detailed or failing to account for energy used in the supply chain and downstream use of a company's products.[143,144,129] Stakeholders have noted the need for transparency in progress towards targets.[8,26]

Box 4: Regulations and standards for ICT

ICT energy efficiency and sustainability is primarily governed by industry standards. There is also some UK legislation.

UK legislation

All ICT hardware is subject to the 2021 Ecodesign for Energy-Related Products and Energy Information Regulations.[145] These outline minimum energy performance standards for products on the UK market (CBP 9302).[146]

Industry standards for ICT

- **Data centre standards:** Standards are set by European (CENELEC/CEN/ETSI) and international (ISO/IEC) standardisation committees.[116] BS-EN50600 is a standards series that includes requirements for data centre energy management and sustainability.[147,148] The EU Code of Conduct (EUCOC) for Data Centres also provides guidelines for energy efficiency.[68,116] Work is ongoing to develop certifications of compliance with standards.[149]
- **Communication network standards:** Standards are set by the European Telecommunications Standards Institute (ETSI) and the ITU.[150,151] These cover different aspects of telecoms infrastructure, such as the EN50173 for cabling.[152] There is also a EUCOC that sets maximum electricity use for broadband equipment.[153,154]
- **Device standards:** The Energy Star labelling informs consumers of the energy efficiency of devices.[155]
- **Cross-sector standards:** An ITU standard released in 2020 sets climate targets for the ICT sector and outlines trajectories towards net zero by 2050.[6]

Consumer behaviour

Some stakeholders note that greater understanding of the energy and environmental impacts of ICT could lead to changes in user behaviour.[26,156] The Energy Savings Trust suggests that consumer electronics make up about 6% of household energy bills and provides advice on how individuals can reduce their energy use of ICT, for example by using laptops instead of desktops.[157,158] Groups have suggested that some other recommendations to individuals discussed in the media, such as sending fewer emails, make relatively little difference to overall ICT energy use.[129,132,159,160] They note that ICT corporations have a responsibility for designing their products and services to be more energy efficient, so that the combined energy use by all consumers is reduced.[161,162]

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 Aimee Ross for researching this briefing, to the STFC for funding her parliamentary fellowship, and to all contributors and reviewers. For further information on this subject, please contact the co-author, Dr Lorna Christie.

References

1. BEIS (2021). Net Zero Strategy: Build Back Greener. *GOV.UK*.
2. DCMS Our Ten Tech Priorities.
3. POST (2021). POSTNote 655: Energy sector digitalisation.
4. Malmodin, J. *et al.* (2018). The Energy and Carbon Footprint of the Global ICT and E&M Sectors 2010–2015. *Sustainability*, Vol 10, 3027. Multidisciplinary Digital Publishing Institute.
5. Andrae, A. S. G. (2020). New perspectives on internet electricity use in 2030. *Eng. Appl. Sci. Lett.*, Vol 3, 19–31.
6. (2020). ITU-T L.1470 (01/2020): Greenhouse gas emissions trajectories for the information and communication technology sector compatible with the UNFCCC Paris Agreement. International Telecommunication Union.
7. Montevecchi, F. *et al.* (2020). Energy-efficient Cloud Computing Technologies and Policies for an Eco-friendly Cloud Market. Final Study Report. Vienna. European Commission.
8. Freitag, C. *et al.* (2021). The real climate and transformative impact of ICT: A critique of estimates, trends, and regulations. *Patterns*, Vol 2, 100340.
9. Malmodin, J. (2020). The power consumption of mobile and fixed network data services - The case of streaming video and downloading large files. *Electron. Goes Green Proc. 2020*,
10. Kamiya, G. (2021). Data Centres and Data Transmission Networks Report. International Energy Agency.
11. (2017). Digitalization and Energy. International Energy Agency.
12. Cisco (2016). United Kingdom - 2020 Forecast Highlights. Cisco.
13. Shehabi, A. *et al.* (2018). Data center growth in the United States: decoupling the demand for services from electricity use. *Environ. Res. Lett.*, Vol 13, 124030.
14. Masanet, E. *et al.* (2020). Recalibrating global data center energy-use estimates. *Science*, Vol 367, 984–986.
15. Cully, J. *et al.* (2022). POSTnote 629: Cloud computing.
16. Corcoran, P. M. (2012). Cloud Computing and Consumer Electronics: A Perfect Match or a Hidden Storm? *IEEE Consum. Electron. Mag.*, Vol 1, 14–19.
17. Samuel, G. *et al.* (2022). The Environmental Sustainability of Digital Technologies: Stakeholder Practices and Perspectives. *Sustainability*, Vol 14, 3791. Multidisciplinary Digital Publishing Institute.
18. Koomey, J. G. *et al.* (2013). Smart Everything: Will Intelligent Systems Reduce Resource Use? *Annu. Rev. Environ. Resour.*, Vol 38, 311–343.
19. RE100 - We are accelerating change towards zero carbon grids at scale. *RE100*.
20. Is Staying Online Costing the Earth? *Policy Connect*.
21. Hintemann, R. (2020). Efficiency gains are not enough: Data center energy consumption continues to rise significantly. Berlin: Borderstep Institute. Borderstep Institute for Innovation and Sustainability.
22. Aslan, J. *et al.* (2018). Electricity Intensity of Internet Data Transmission: Untangling the Estimates. Social Science Research Network.
23. Coroama, V. (2021). Investigating the Inconsistencies among Energy and Energy Intensity Estimates of the Internet. Metrics and Harmonising Values. *Swiss Fed. Off. Energy SFOE Bern Switz.*,
24. (2022). Mobile Net Zero: State of the Industry on Climate Action 2022 report. GSMA.
25. Annual reports - Financial reporting & news - Investors | BT Plc.
26. The Royal Society (2020). Digital technology and the planet: harnessing computing to achieve net zero. 130.
27. Lange, S. *et al.* (2020). Digitalization and energy consumption. Does ICT reduce energy demand? *Ecol. Econ.*, Vol 176, 106760.
28. Horner, N. C. *et al.* (2016). Known unknowns: indirect energy effects of information and communication technology. *Environ. Res. Lett.*, Vol 11, 103001. IOP Publishing.
29. Kaack, L. H. *et al.* (2022). Aligning artificial intelligence with climate change mitigation. *Nat. Clim. Change*, Vol 12, 518–527. Nature Publishing Group.
30. Smartphones replacement cycle in the US 2014-2025. *Statista*.
31. (2019). The hidden cost of your smartphone. *Which? News*.
32. Shehabi, A. *et al.* (2016). United States Data Center Energy Usage Report. Lawrence Berkeley National Lab. (LBNL), Berkeley, CA (United States).
33. Fryer, E. (2018). Data centres and heat reuse: Light at the end of the tunnel? techUK.
34. (2012). Is Cloud Computing Always Greener? Natural Resources Defense Council.
35. What Is a Hyperscale Data Center? *Vertiv*.
36. Bashroush, R. *et al.* (2018). Datacenter EURECA Project Final Report. EURECA.
37. The calculation of electricity use equivalent assumes a global average of 0.6 kgCO2e per kWh as per the Ericsson 2018 study.
38. Fryer, E. (2020). The UK Data Centre Sector. techUK.
39. Schien, D. *et al.* (2021). Using behavioural data to assess the environmental impact of electricity consumption of alternate television service distribution platforms. *Environ. Impact Assess. Rev.*, Vol 91, 106661.
40. Baker, C. *et al.* (2022). Gigabit-broadband in the UK: Government targets and policy.
41. (2021). Connected Nations 2021. *Ofcom*.
42. Our network - Coronavirus | BT Plc.
43. Ritchie, H. *et al.* (2020). Energy. *Our World Data*,
44. Joint Research Centre (European Commission) *et al.* (2017). Proceedings of the 9th international conference on energy efficiency in domestic appliances and lighting (EEDAL '17). Part I. Publications Office of the European Union.
45. Belkhir, L. *et al.* (2018). Assessing ICT global emissions footprint: Trends to 2040 & recommendations. *J. Clean. Prod.*, Vol 177, 448–463.
46. Roser, M. *et al.* (2013). Technological Change. *Our World Data*,
47. (2020). A Decade of Change: How Tech Evolved in the 2010s and What's In Store for the 2020s. *Global X ETFs*.
48. Alcott, B. (2005). Jevons' paradox. *Ecol. Econ.*, Vol 54, 9–21.
49. Sorrell, S. (2009). Jevons' Paradox revisited: The evidence for backfire from improved energy efficiency. *Energy Policy*, Vol 37, 1456–1469.
50. Moore's Law Explained. *Investopedia*.
51. Koomey, S. N., Jonathan (2016). Energy Efficiency of Computing: What's Next? *Electronic Design*.
52. Shalf, J. (2020). The future of computing beyond Moore's Law. *Philos. Trans. R. Soc. Lond. Ser. A*, Vol 378, 20190061.
53. Koot, M. *et al.* (2021). Usage impact on data center electricity needs: A system dynamic forecasting model. *Appl. Energy*, Vol 291, 116798.
54. Bashroush, R. *et al.* (2022). Optimizing Server Refresh Cycles: The Case for Circular Economy With an Aging Moore's Law. *IEEE Trans. Sustain. Comput.*, Vol 7, 189–200.
55. Fernandez, A. D. *et al.* (2017). Quantum Technologies.

56. Materials for Low Loss Electronics. *Henry Royce Institute*.
57. Application-Specific Integrated Circuit (ASIC) Miner. *Investopedia*.
58. What Is a GPU? Graphics Processing Units Defined. *Intel*.
59. (2021). Software-Hardware Co-Design Becomes Real. *Semiconductor Engineering*.
60. (2022). Sustainable Software Engineering (SSE) and the role and responsibilities of a Sustainable Software Engineer. *Sustainable Software*.
61. Responsible Computing. *RC*.
62. Principles of Green Software Engineering. *Principles Green*.
63. (2022). Green Software Foundation Releases Q1 2022 Report. *Green Software Foundation*.
64. Podder, S. *et al.* (2020). How Green Is Your Software? *Harvard Business Review*.
65. Shehabi, A. *et al.* (2016). United states data center energy usage report.
66. (2017). Small Data Centers, Big Energy Savings: An Introduction for Owners and Operators. Better Buildings Solution Center, US Department of Energy.
67. (2015). The Problem of Inefficient Cooling in Smaller Data Centers. *Data Center Knowledge*.
68. Bertoldi, P. *et al.* (2022). 2022 Best Practice Guidelines for the EU Code of Conduct on Data Centre Energy Efficiency. JRC.
69. DeepMind AI Reduces Google Data Centre Cooling Bill by 40%.
70. (2021). To cool datacenter servers, Microsoft turns to boiling liquid. *Innovation Stories*.
71. Fryer, E. (2019). UK Data Centre Sector Energy Routemap. techUK.
72. Miller, J. (2020). POSTnote: Heat Networks. POST.
73. Werner, S. (2017). District heating and cooling in Sweden. *Energy*, Vol 126, 419–429.
74. Biba, E. The city where the internet warms people's homes.
75. Harriss, L. (2022). POSTbrief: Telecommunications Infrastructure: Cabling, Ducts and Poles. POST.
76. Breide, S. *et al.* (2021). Energy consumption of telecommunication access networks. Prysmian Group.
77. Jackson, M. (2020). Study Finds Full Fibre is the Most Energy Efficient Broadband. *ISPreview UK*.
78. Gladisch, A. *et al.* (2008). Power efficiency of optical versus electronic access networks. in *2008 34th European Conference on Optical Communication*. 1–4.
79. Lundén, D. *et al.* (2022). Electricity Consumption and Operational Carbon Emissions of European Telecom Network Operators. *Sustainability*, Vol 14, 2637. Multidisciplinary Digital Publishing Institute.
80. Christie, L. (2018). POSTbrief: Distributed Ledger Technology.
81. Cambridge Bitcoin Electricity Consumption Index (CBECI).
82. EDNA Publishes Policy Brief on Blockchain Energy Consumption. *4E Energy Efficient End-use Equipment*.
83. Bitcoin. Change the code, not the climate.
84. Kamiya, G. (2019). Bitcoin energy use - mined the gap – Analysis.
85. Coroama, V. (2021). Blockchain energy consumption. An exploratory study. *Swiss Fed. Off. Energy SFOE Bern Switz.*, 40.
86. Platt, M. *et al.* (2021). The Energy Footprint of Blockchain Consensus Mechanisms Beyond Proof-of-Work. *2021 IEEE 21st Int. Conf. Softw. Qual. Reliab. Secur. Companion QRS-C*, 1135–1144.
87. Proof-of-stake (PoS). *ethereum.org*.
88. West, C. *et al.* (2019). Cyber Security of Consumer Devices. 6. POST.
89. Global IoT and non-IoT connections 2010-2025. *Statista*.
90. Strathern, F. (2021). IoT technology will save eight times the energy it consumes by 2030, new report shows. *Internet of Things News*.
91. Das, S. *et al.* (2020). The global energy footprint of information and communication technology electronics in connected Internet-of-Things devices. *Sustain. Energy Grids Netw.*, Vol 24, 100408.
92. Pirson, T. *et al.* (2021). Assessing the embodied carbon footprint of IoT edge devices with a bottom-up life-cycle approach. *J. Clean. Prod.*, Vol 322, 128966.
93. Christie, L. (2022). POSTnote: Interpretable machine learning. POST.
94. National AI Strategy - HTML version. *GOV.UK*.
95. Strubell, E. *et al.* (2019). Energy and Policy Considerations for Deep Learning in NLP. *ArXiv190602243 Cs*,
96. Schwartz, R. *et al.* (2019). Green AI. *ArXiv190710597 Cs Stat*,
97. Wu, C.-J. *et al.* (2022). Sustainable AI: Environmental Implications, Challenges and Opportunities. *ArXiv211100364 Cs*,
98. Christie, L. (2019). POSTbrief: 5G Technology. POST.
99. Schubert, N. (2021). NGMN Identifies Key Energy Saving Solutions for Mobile Networks. *NGMN*.
100. 5G Power: Creating a green grid that slashes costs, emissions & energy use. *huawei*.
101. Curtailing carbon emissions – Can 5G help? *STL Partners*.
102. Williams, L. *et al.* (2022). The energy use implications of 5G: Reviewing whole network operational energy, embodied energy, and indirect effects. *Renew. Sustain. Energy Rev.*, Vol 157, 112033.
103. Abecassis, D. *et al.* (2019). Global race to 5G Update. Analysis Mason.
104. 5G: The Risks and Rewards for Operators.
105. Jackson, M. (2021). All Public 2G and 3G UK Mobile Services Switched Off by 2033. *ISPreview UK*.
106. A joint statement on the sunsetting of 2G and 3G networks and public ambition for Open RAN rollout as part of the Telecoms Supply Chain Diversification Strategy. *GOV.UK*.
107. Off mode, standby and networked standby. *European Commission - European Commission*.
108. Zaidi, A. (2017). Three design principles of 5G New Radio. *Ericsson*.
109. (2020). 5G and energy efficiency: new mechanisms for progress. *Hello Future*.
110. Cully, J. *et al.* (2022). Edge computing.
111. Data Center 2025: Closer to the Edge.
112. (2021). Is edge computing good or bad for the planet? *Tech Monitor*.
113. (2019). How much energy does the cloud need? *Borderstep Institute*.
114. Hamm, A. *et al.* (2020). Edge Computing: A Comprehensive Survey of Current Initiatives and a Roadmap for a Sustainable Edge Computing Development. 15.
115. Daley, S. Putting edge computing centre stage in the UK's fourth industrial revolution. *Computer Weekly*.
116. Brocklehurst, F. (2022). International review of energy efficiency in Data Centres for IEA EBC Building Energy Codes Working Group. IEA EBC Building Energy Codes Working Group.
117. Energy Savings Opportunity Scheme (ESOS). *GOV.UK*.
118. Environmental reporting guidelines: including Streamlined Energy and Carbon Reporting requirements. *GOV.UK*.

119. Department for Environment, Food and Rural Affairs (2021). Greening Government Commitments 2021 to 2025.
120. Greening government commitments 2019 to 2020 annual report. *GOV.UK*.
121. EURECA.
122. (2021). Sustainability Report 2020. Facebook.
123. (2021). Amazon Sustainability Report 2020. Amazon.
124. (2021). Alphabet's 2021 CDP Climate Change Response. Alphabet.
125. (2022). Apple Environment Report. Apple.
126. (2021). Microsoft 2021 Environmental Sustainability Report. Microsoft.
127. (2020). Digital Realty Environmental, Social and Governance Report. Digital Realty.
128. (2021). Equinix Sustainability Report 2020. Equinix.
129. Preist, C. *et al.* (2019). Evaluating Sustainable Interaction Design of Digital Services: 2019 CHI Conference on Human Factors in Computing Systems, CHI 2019. *CHI 2019 - Proc. 2019 CHI Conf. Hum. Factors Comput. Syst.*, 1–12. Association for Computing Machinery (ACM).
130. Bashroush, Rabih Despacito Streaming Energy Consumption.
131. About DIMPACT - DIMPACT.
132. Carbon Trust, DIMPACT (2021). Carbon impact of video streaming.
133. Bolton, P. *et al.* (2022). Support for low carbon power.
134. Plans unveiled to decarbonise UK power system by 2035. *GOV.UK*.
135. Fryer, E. (2016). Climate Change Agreement (CCA) for Data Centres. Target Period One.
136. Climate change agreements. *GOV.UK*.
137. Seely, A. (2022). Climate change levy.
138. Seely, A. *et al.* (2022). Climate Change Levy: renewable energy & the carbon reduction commitment.
139. Fryer, E. (2017). Climate Change Agreement (CCA) for Data Centres. Target Period Two: Report on Findings. techUK.
140. Who's in Race to Zero? | UNFCCC.
141. Science Based Targets - Information and Communication Technology (ICT). *Science Based Targets*.
142. (2020). Guidance for ICT Companies Setting Science Based Targets. ITU, GESI, GSMA, SBTI.
143. Calma, J. (2022). Big Tech's climate goals are weaker than they seem, report finds. *The Verge*.
144. Corporate Climate Responsibility Monitor 2022. *NewClimate*.
145. Department for Business, Energy & Industrial Strategy (BEIS) (2021). Regulations: energy information. *GOV.UK*.
146. Conway, L. (2022). Right to Repair Regulations.
147. Data Centre, Sustainability & Smart City Standards – Carbon 3.
148. Information technology - Data centre facilities and infrastructures. BSI British Standards.
149. (2019). DCA spotlight: Data centre certification – good, bad or ugly? *Intelligent Data Centres*.
150. ETSI - Welcome to the World of Standards!
151. ITU ITU-T Recommendations and other publications. *ITU*.
152. CENELEC - EN 50173-1. *Engineering360*.
153. E3P, T. (2016). Broadband Communication Equipment Codes of Conduct.
154. Bertoldi, P. *et al.* (2021). Code of Conduct on Energy Consumption of Broadband Equipment. *JRC Publications Repository*.
155. ENERGY STAR.
156. Haider, U. (2019). DCW Frankfurt 2019: Conspicuous cloud consumption in the digital era. *Techerati*.
157. Guide to choosing home appliances - Energy Saving Trust.
158. Woodward, K. (2022). Top five energy consuming home appliances. *Energy Saving Trust*.
159. Nast, C. YouTube's carbon footprint is huge, but smarter web design could fix it. *Wired UK*.
160. (2020). Climate change: Can sending fewer emails really save the planet? *BBC News*.
161. Griggs, M. B. (2019). YouTube could help the planet by throwing out its digital waste. *The Verge*.
162. Bashroush, R. *et al.* (2017). Architectural Principles for Energy-Aware Internet-Scale Applications. *IEEE Softw.*, Vol 34, 14–17.