Digital technology and the planet

Harnessing computing to achieve net zero

THE ROYAL SOCIETY

Digital technology and the planet: Harnessing computing to achieve net zero
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Erratum: The first edition of this report incorrectly stated there were no data centres from Google, Amazon or Microsoft in the UK, while there are at least two from Microsoft. This error has been corrected on p74. The first edition also stated that 'If individuals keep their phones for four years instead of two, this contribution is halved', which was corrected on p75 to 'Keeping phones for twice as long can significantly reduce this share of emissions'. The conclusions of this report remain unchanged.

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Foreword

Digital technology is embedded in our daily lives and in every sector, so it has a critical and growing part to play in delivering a net zero future. Nearly a third of the 50% carbon emissions reductions the UK needs to make by 2030 could be achieved through existing digital technology – from sensors to large-scale modelling. For example, digital twins – virtual representations of physical assets – have already helped increase the yield of some wind farms by up to 20%, as well as improved their life span.

Maximising digital technology's contribution to the net zero 2050 target will depend on the policy decisions we make today, and the actions of governments, industry and funders.

In 2021, the UK will host COP26 and assume presidency of the G7, this is a chance to lead the global response to climate change and further, connected, environmental challenges such as biodiversity loss. The UK has the opportunity to drive robust data-driven approaches towards achieving a reliable carbon credits market internationally, with a focus on supporting developing economies.

While there are many routes to net zero, digital technologies are central to all modern economies. The UK should use its position to show how digital technology can underpin change across every sector. Departments and local authorities should draw up plans for using tech to reach net zero, and to acquire the skills to make it a reality.

The use of digital technologies is growing rapidly, and has been accelerated in this pandemic, but their energy use has grown much more slowly. Efficiencies in data centres over the past decade mean that overall their energy consumption has stayed level despite rising demand. At the same time, the switch to digital often, but not always, removes the need and associated emissions of a physical meeting, product, or service.

The tech sector is in a position to lead by example. It can manage its own carbon footprint, for instance by scheduling computing jobs at times of peak power production, to make the best use of renewable sources. To allow transparency and wider planning, the tech sector should make public the data on its own emissions.

The tech industry should also ensure the energy use of infrastructure development and technology applications is proportionate. Regulators can also provide guidance on this matter. One particularly striking example is bitcoin, which wastes huge amounts of energy in its generation. As technologies emerge and evolve we should ensure energy proportionality is baked in from the very first lines of code.

Government should use the net zero target to drive momentum behind the provision of data access, digital infrastructure and skills. In Spring 2020, only 12% of UK homes and offices had access to full-fibre broadband. In the recovery from the pandemic, there is an imperative to close the digital divide and skills gaps, giving people the chance to get back to meaningful jobs across the country.

The scale of the net zero challenge demands new models for innovation be explored, including an ecosystem supporting open repositories of intellectual property and rewarding high-risk challenge-led research. Government, funders, industry and academia – from computer science to social sciences – must combine research and development efforts to greater effect.

I am a firm believer in the unbelievable truth. Time and again in my career, I have seen technological innovation turn insurmountable problems into everyday marvels we soon take for granted. Climate change is among the greatest challenges facing our species, and while digital technology is just one part of the solution, it is absolutely central to the net zero future we must build.

Professor Andy Hopper CBE FREng FRS, Chair, *Digital technology and the planet* Working Group, Treasurer and Vice-President of the Royal Society.

Executive summary

Urgent, sustained, collective action is needed in order to address the global climate emergency. As communities across the world recover from the COVID-19 crisis, efforts to reignite economies should be harnessed to accelerate the shift to a net zero economy and society.

Digital technologies have already transformed the economy. Digital services have revolutionised communications and made it possible for a large part of the economy to continue to function during the pandemic. Data-enabled technologies such as machine learning and artificial intelligence have also enabled efficiencies and optimisation across sectors. While some of these applications already contribute to reductions in greenhouse gas emissions, digital technologies also have an environmental cost which should not be neglected – from the extraction of minerals to the energy use and emissions of the technology.

Under the right conditions, digital technologies could optimise and reduce their own footprint and bring even more transformative changes, triggering a bigger switch beyond optimisation. They can help promote a shift towards low-carbon ways of living and working – enabling individuals to adopt 'greener' lifestyles, from how they travel to how they heat their homes. At a systems level, 'digital twins' could generate rich data flows enabling a 'control loop' for the planet's emissions which would allow much better planning, monitoring and control of the world's emissions. Digital twins, combined with artificial intelligence and deployed at a national or planetary scale, will also be important for optimisation and stress testing. Digital technologies like machine learning also provide new tools to society including for scientists, social scientists, and policy makers. They have an enabling role, for example in underpinning smart machines and, crucially, in advancing research and innovation, where they could help discover brand new solutions to the net zero challenge.

The UK is in a position to drive this change, building on its world-leading research in digital technology and other disciplines, and vibrant tech start-up ecosystems. However, technology alone will not achieve the transition to a low-carbon economy. While digital technologies offer the promise to catalyse change, wider policies – including those on sustainability – will be vital to set a direction towards low-emissions ways of living and working, and to shape technology development to deliver positive outcomes for the planet. The right policies will also be needed to create critical digital infrastructures for net zero, that work for everyone. Action in key areas will help secure the transformation: building a trusted data infrastructure for net zero; optimising our digital carbon footprint; establishing a data-enabled net zero economy; setting research and innovation challenges to digitise the net zero transition.

Digital systems from ground sensors to satellites can generate valuable data, enabling greater emissions monitoring and understanding of climate trends and intervention impacts. This, together with data from across sectors about the inner workings of these sectors, from the mapping of physical assets to business processes, can power data-driven systems and services with the potential to achieve significant emission reductions across the economy – from underpinning the smart control of energy networks, to enabling a switch to 'as a service' business models and a circular economy.

There is already a wealth of relevant, existing data which could be used more widely now, provided they are made findable, accessible, interoperable and reusable. There may also be a case for the collection and analysis of new data, for example emissions data with greater temporal and spatial definition. Safe and rapid use of data to support the achievement of net zero will require the appropriate data governance and data sharing institutions. Building a reliable and comprehensive data infrastructure should be a priority.

Data-driven systems for net zero must be taken up across society and the economy, and to be trusted they will need to work for everyone. The design and deployment of data-driven systems for net zero should be inclusive and grounded in engagement with all stakeholders and communities affected by their use. These systems should be developed and applied in a way that allows contestation, meaning that it is possible to challenge and verify their output because they are transparent and explainable for example. As a number of these systems are critical digital infrastructure for the planet, they need to be safe, robust and resilient.

A wide range of estimates have been published for the carbon footprint of digital systems themselves, but further work is needed to evaluate the potential climate impact of increasing use of digital technologies. To allow greater monitoring and scrutiny, data about the energy consumption and emissions associated with the whole life cycle of digital technologies should be made widely available. Data centres are increasingly running on clean energy and could further help the uptake of intermittent renewable energy sources, by scheduling computing at times of peak renewable production.

Digital technologies developed and deployed in pursuit of net zero must be energy-proportionate – ie they must bring environmental or societal benefits that outweigh their own emissions.

With the right incentives, applications of digital technologies could bring about new services and business models allowing a shift away from resource consumption and carbon-intensive wealth creation. The transformation towards a data-enabled net zero economy also promises to create many local jobs. To secure a net zero transition that works for all, building digital skills and net zero knowledge at all levels should be a priority.

A number of research and innovation challenges are still to be solved to deliver the potential of digital technologies in achieving a net zero economy and society. These include better integrating energy and digital systems, prototyping data infrastructure, developing trustworthy digital systems, green computing, enabling nature-based and engineering-based mitigation approaches, understanding drivers influencing societal transformation and distributing fairly the cost and benefits of the transition to net zero. Data, in conjunction with technologies such as artificial intelligence and digital twins, should be at the heart of the net zero transition. Achieving the promise of this data-led net zero transition will require an ambitious, collaborative and challenge-led research and innovation effort.

Recommendations

AREA FOR ACTION: BUILDING A TRUSTED DATA INFRASTRUCTURE FOR NET ZERO

Data will be at the core of the net zero transition, enabling emissions monitoring as well as data-driven applications and services underpinning emission savings across sectors. For digital technologies deployed in the context of net zero to work for everyone, they will need to enable individuals and society to scrutinise their outputs and methods, they must be secure and resilient, and there must be a wide engagement of all stakeholders.

RECOMMENDATION 1

The net zero transition should be data-led, with governance arrangements in place that enable the safe and rapid use of data to support the achievement of the net zero target:

- As part of the COP26 effort and future international engagement, the UK Government should lead on the creation of international arrangements to enable the collection, sharing and use of data to underpin the development of applications and services helping achieve net zero. A key aspiration should be the establishment of a flow of data making planetary digital twins and a control loop for the planet possible. For the latter, data about a number of essential climate variables need to be made more widely available, for example measured atmospheric composition and concentration, and rainfall data, which is important for estimating the future land carbon sinks and should be shared widely on a global level.
- To ensure the transition towards a low-carbon economy harnesses the potential of data and digital technology, there needs to be coordination between initiatives happening across government, regulators, industry and the third sector. To this end, the UK Government should be informed by a cross-departmental and cross-sector taskforce devoted to the digitalisation of the net zero transition[1] and ensuring these initiatives are connected and amplified. It should identify immediate policy interventions and develop a roadmap for the digitalisation of the net zero transition, setting out priority use cases for existing data, actions to increase data access and use, and priorities regarding new data collection and analyses. It should ensure that data that can help achieve net zero follow the FAIR principles (Findable, Accessible, Interoperable, Reusable).

1. The digitalisation of the net zero transition means a transition that involves collecting quality data on emissions and energy use and that uses that data to create innovative solutions and bring down energy use and emissions. A transition that makes the greatest use of digital technology and digital services to reduce energy use and emissions, in ways that serve all of society. Also see Box 1.

- Data for emissions monitoring: In order to accelerate the systematic collection of robust data about businesses' energy use and emissions across sectors, the taskforce for the digitalisation of the net zero transition should work with the science community and business to review standards for reporting Scope 1, Scope 2, and Scope 3 greenhouse gas emissions – respectively associated with energy use, the energy mix involved, and upstream and downstream emissions. This should consider the temporal and spatial sampling of published data that would support greater monitoring of supply chain emissions and intervention impacts.
- Data that can help achieve net zero should be made accessible through appropriate arrangements. Wherever possible it should be made open, while adequately addressing social and ethical dilemmas in data use. Where data cannot be made fully open, appropriate and robust frameworks should be in place, such as data access agreements or data trusts. In the case of datasets containing sensitive data, data might be made more shareable through privacy-preserving approaches including anonymisation, synthetic data generation and other approaches. For example, smart meter data should be made open after applying differential privacy or equivalent approaches to prevent the identification of any single household.

RECOMMENDATION 2

The UK Government has a responsibility to set an example of best practice through well governed use of data.

When implementing the National Data Strategy, Government should ensure data strategies and data standards across government departments and regulators function to facilitate data use and promote trustworthy technology use. This should build on the Centre for Data Ethics and Innovation's work on public sector data sharing, to overcome barriers to data sharing and address citizen trust. Through low-carbon, outcome-focused procurement and through sponsoring pathfinder studies, Government can lead the way in driving development and adoption of digital technologies for net zero, modelling their use for others and engaging regulatory bodies in identifying the data sharing agreements and other frameworks needed to support such applications.

RECOMMENDATION 3

The UK Government, through a taskforce set up to connect and amplify cross-departmental and cross-sector initiatives on the digitalisation of the net zero transition, should enable industry, in particular the larger tech companies, as well as regulators and the third sector to ensure:

- Data-driven systems for net zero be developed to allow people to inspect and challenge their output. There should be a concerted effort to set standards to support contestation: data-driven systems to achieve net zero should be explainable, transparent, and auditable.
- Digital systems for net zero be developed to be secure and resilient. A collaborative effort should set resilience standards for data-driven systems deployed to achieve net zero: they should be able to work on a range of scales, be cybersecure, interoperable, flexible, safe and robust.
- Digital systems benefit the communities into which they are deployed. A collaborative effort should involve affected communities in order to develop a shared understanding of the purpose of technologies deployed in the context of net zero and to co-design approaches to navigate the associated dilemmas. This requires careful design of the interface between people and technology, and consideration of the societal impact of such technologies. Participatory design should play a central role in shaping and delivering digital solutions to the net zero challenge.

AREA FOR ACTION: OPTIMISING OUR DIGITAL CARBON FOOTPRINT

Keeping track of the tech sector's own carbon footprint will require greater data availability. The sector's footprint can be reduced through multiple approaches, including the further uptake of renewables and the scrutiny of digital technologies' energy proportionality – ie whether specific data and computing applications bring environmental or societal benefits that outweigh their own emissions.

RECOMMENDATION 4

The tech sector should lead by example and make data accessible to allow the greater monitoring of its energy consumption and carbon emissions.

Government leaders should identify the levers to ensure tech companies share publicly data about the energy consumptions of their digital systems and products, including embodied and use phase emissions, in particular from data centres – this should include Scope 1, 2 and 3 emissions. This should be part of the National Data Strategy and could build on Defra's Greening Government: ICT and Digital Services Strategy. This would involve the Department for Digital, Culture, Media and Sport (DCMS), the Department for Business, Energy and Industrial Strategy (BEIS) and HM Treasury working together to identify and establish those levers.

RECOMMENDATION 5

Tech companies should further promote the use of renewable energy for computing activities, for example by scheduling these activities, where appropriate, for times that maximise the use of intermittent renewable energy sources.

RECOMMENDATION 6

Regulators should develop guidance about the energy proportionality of digital applications.

Such guidance could set out key questions to consider when developing or deploying digital technologies. Where there are options to use less energy-intensive approaches, guidance should make this clear. For example, the Financial Conduct Authority should provide guidance on the energy intensity of blockchain-based applications used in financial systems.

AREA FOR ACTION: ESTABLISHING A DATA-ENABLED NET ZERO ECONOMY

Rebuilding the economy after the COVID-19 pandemic should focus on building a low-carbon economy, utilising data and digital technologies to achieve this. A focus on skills is essential to enable everyone to take part and accelerate a data-enabled net zero transition. COP26 presents an opportunity for the UK to demonstrate leadership in the digitalisation of the net zero transition and secure global change.

RECOMMENDATION 7

Action is needed to build digital and net zero skills at all levels – from basic literacy to advanced data analysis skills, and from an appreciation of efficiency to an in-depth understanding of carbon externalities. Re-tooling the workforce in this way will require a coordinated approach to nurturing data science and net zero skills across the country.

- The National Data Strategy, developed by DCMS, should prioritise action to equip the UK with the skills to drive a data-enabled net zero revolution, and DCMS could prioritise the use of data for net zero within the National Data Strategy missions.
- BEIS' and the Ministry for Housing, Communities and Local Government's (MHCLG) joint Cities and Local Growth policy team should prioritise skills for a data-enabled net zero economy at the local level, providing annual reports on progress in increasing digital skills in local communities. Local Enterprise Partnerships should push digital skills in the local economy, for example by auditing whether universities and local employers are collaborating to identify and meet local digital skills and net zero skills needs.
- To support the development of a data-enabled net zero economy across the country, research institutes, the Energy Systems Catapult and Digital Catapult, learned societies and charities should provide information resources and toolkits to support local energy and environmental initiatives led by volunteers or social enterprises. There is also a role for training providers to develop agile and nimble opportunities for individuals to reskill and upskill as the nature of their job changes due to digitalisation.

RECOMMENDATION 8

The UK Government should use COP26 as an opportunity to lead the way in establishing ambitious programmes that bring together governments, industry and the third sector – committing funding, data, skills, and computing facilities – to develop computing as infrastructure for the planet.

The UK Government could put forward an initiative on a robust data-driven approach towards achieving a reliable carbon credits market internationally, with a focus on supporting developing economies.

AREA FOR ACTION: SETTING RESEARCH AND INNOVATION CHALLENGES TO DIGITALISE THE NET ZERO TRANSITION

A number of research and innovation challenges need addressing in order to realise the full potential of the digitalisation for net zero. This calls for an urgent and ambitious collaborative research and innovation effort.

RECOMMENDATION 9

The UK Government's policies should be updated to reflect the net zero imperative.

For example the Clean Growth Strategy and Industrial Strategy Challenge Funds on artificial intelligence (AI) should explicitly seek to harness the digital revolution and direct research and development activities to achieve climate goals. To boost collaboration to tackle climate change, and to increase university-business connectivity in particular, Challenge Funds should comprise collaborative grants and large programmes of interconnected grants.

RECOMMENDATION 10

Regulators should provide frameworks to help business innovating in the space of digital applications for net zero, acknowledging the need for a step change in innovation to adapt to the net zero agenda and enable the green recovery.

This can be based on adaptive regulations and regulatory sandboxes that provide space for experimentation. For example, Ofgem announced an expansion of its regulatory sandbox service to support innovative services and business models contributing to the decarbonisation of energy. There is an opportunity for regulators across sectors to build on this work.

RECOMMENDATION 11

Creating a stronger innovation ecosystem for net zero and distributing the benefits: Government should use new models of challenge-led innovation to tackle the net zero challenge, with a greater focus on digitalisation.

These should consider a balanced portfolio of risk, including 'high-risk, high-reward' research, and should be based on a lean structure in which qualified research and innovation programme leaders appointed on a fixed-term basis are given greater discretion over the programmes that they select.

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Introduction

Harnessing digital technologies for the future of the planet

The coming years will be a critical time for the state of the planet and human wellbeing, as climate change challenges current ways of living and working. Global mean surface temperature is now over 1°C higher than the late 19th century and is set to increase further in the future, with the temperature trajectory dependent on future global greenhouse gas emissions[2]. Continuing on the current emissions pathway could result in a global average temperature increase of several degrees, contributing to severe extreme weather events and long-term sustained sea-level rise.

Governments around the world have committed to taking action to keep global average temperature increases to well below 2°C, and to pursue efforts towards 1.5°C[3]. To achieve this, global greenhouse gas emissions[4] will need to be reduced to net zero, meaning that as much greenhouse gas is removed as added to the atmosphere each year by the middle of the century or shortly thereafter, and then reach negative emissions, meaning more removals than gross emissions[5]. Real zero – no emissions – will need to be achieved in almost all sectors of the economy. The UK Government has set its contribution to the global objective, with a commitment to achieve net zero greenhouse gas emissions by 2050[6]. Scotland committed to achieving net zero emissions by 2045[7]. Achieving these targets will require urgent, ambitious and concerted action to deliver rapid reductions in emissions.

Digital technology can play a role in helping achieve this goal by enabling a shift towards zero-carbon solutions. In the face of potentially catastrophic climate change, attention is increasingly turning to the potential of digital technologies as a tool for reducing and controlling emissions[8].

Recent years have brought rapid advances in digital technologies and expansion of their applications, transforming daily lives and the economy. Algorithms now calculate the fastest routes on maps, analyse medical images to detect diseases, and discover new astronomical phenomena. These advances in digital capabilities and applications will continue, reaching more people in new ways. The total number of internet users around the world, for example, was projected to grow from 3.9 billion in 2018 to 5.3 billion by 2023 (a jump from 51% to 66% of the global population)[9].

51% of the world population were using the internet in 2018. In 2023, it is set to jump to 66%.

2. The Royal Society 2019 Climate change briefings (see https://royalsociety.org/topics-policy/projects/royal-society-climate-change-briefings/, accessed 14 October 2020)
3. United Nations Framework Convention on Climate Change 2015 Paris Agreement (see https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf, accessed 14 October 2020)
4. Greenhouse gas emissions comprise of principally carbon dioxide, but also methane, nitrous oxide, and a range of smaller concentration trace gases such as the so-called group of 'F-gases'.
5. Intergovernmental Panel on Climate Change 2018 Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (see https://www.ipcc.ch/sr15/, accessed 14 October 2020)
6. UK Government 2019 UK becomes first major economy to pass net zero emissions law (see https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law, accessed 14 October 2020)
7. Scottish Government 2019 Climate Change Act (see www.gov.scot/policies/climate-change/reducing-emissions/, accessed 25 November 2020)
8. The Royal Society 2020 Digital technologies and human transformations (see https://royalsociety.org/topics-policy/publications/2020/digital-technologies-and-human-transformations/, accessed 14 October 2020)
9. Cisco 2020 Cisco Annual Internet Report (2018–2023) (see https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.pdf, accessed 14 October 2020)

As digital technologies become increasingly pervasive, there will be new opportunities to apply them in pursuit of the net zero target. However, technology alone will not achieve the transition to a low-carbon economy that will be necessary to achieve net zero. While digital technologies offer the promise to catalyse change, wider policies – including those on sustainability – will be vital to set a direction towards greener ways of living and working, and to shape technology development towards positive outcomes for the planet[10]. Digital technologies provide potentially valuable tools, but the context in which they are developed and deployed will determine the extent to which they will serve environmental goals. An important factor will be the ability of many segments of the population to interact with and use these technologies.

Terms of reference and conduct of the study

The Royal Society is working to create the conditions for the safe and rapid use of data and digital technology. A series of major reports have identified the interventions necessary to support a resilient and trustworthy digital system for the UK[11], create an environment of careful stewardship of machine learning technologies[12], strengthen the UK's data science talent base[13], and govern data use in ways that promote human flourishing[14,15]. Recognising the opportunity to harness the power of these technologies for the benefit of society, in November 2019 the Society initiated a new policy study investigating the potential of digital technologies to help tackle climate change.

The Royal Society's Digital technology and the planet project set out to:

- Investigate the ways in which digital technologies can be mobilised to tackle climate change, both in terms of the development of 'greener' digital systems and their application to reduce carbon emissions;
- Explore pathways for the development of trustworthy digital systems to support efforts to reduce carbon emissions, and the policies that can help advance their development and use; and
- Create a vision for the future of digital technologies deployed in support of reducing carbon emissions.

10. Falk J *et al* 2020 Exponential Roadmap 1.5.1, Scaling 36 solutions to halve emissions by 2030 (see https://exponentialroadmap.org/, accessed 14 October 2020)
11. The Royal Society 2016 Progress and Research in Cybersecurity: supporting a resilient and trustworthy system for the UK (see https://royalsociety.org/-/media/policy/projects/cybersecurity-research/cybersecurity-research-report.pdf, accessed 14 October 2020)
12. The Royal Society 2017 Machine learning: the power and promise of computers that learn by example (see https://royalsociety.org/-/media/policy/projects/machine-learning/publications/machine-learning-report.pdf, accessed 14 October 2020)
13. The Royal Society 2019 Dynamics of data science skills: How can all sectors benefit from data science talent? (see https://royalsociety.org/-/media/policy/projects/dynamics-of-data-science/dynamics-of-data-science-skills-report.pdf, accessed 14 October 2020)
14. The British Academy and The Royal Society 2017 Data management and use: Governance in the 21st century (see https://royalsociety.org/-/media/policy/projects/data-governance/data-management-governance.pdf, accessed 14 October 2020)
15. The Royal Society 2019 Protecting privacy in practice: the current use, development and limit of Pribacy Enhancing Technologies in data analysis (see https://royalsociety.org/-/media/policy/projects/privacy-enhancing-technologies/privacy-enhancing-technologies-report.pdf, accessed 14 October 2020)

There are many potential applications of digital technology for climate change mitigation and adaptation, from informing biodiversity tracking and management to supporting scientific discovery in materials science so as to more effectively capture and store energy[16]. Whilst recognising the importance of other environmental aspects, this study focuses on greenhouse gas emissions and how digital technologies can support the net zero agenda, considering all forms of digital technology that might contribute to reducing or controlling emissions, from hardware to artificial intelligence (AI).

This report was developed with input from a broad range of stakeholders, convened in a series of evidence gathering events (see Appendix). It describes a future where critical digital infrastructure will support 'control loops' enabling the reduction, optimisation and control of emissions across sectors. Scaled to global level, this raises the possibility of a control loop for the planet (see Figure 1 and Box 1). A better connected system with global optimisation would yield better overall solutions, beyond the local optima for each part of the system on its own.

The report considers the action needed to realise the potential of data and digital technology to tackle climate change by reducing emissions across sectors, through a digitalisation of the net zero transition (see Box 1). Chapter 1 illustrates the ways in which digital technologies could transform sectors towards net zero and support low-carbon ways of living and working. Chapter 2 sets out the data and digital infrastructure needed to support the digital transformation for net zero. Chapter 3 considers the characteristics that technologies will need to demonstrate if they are to be deployed as decision-making tools and critical digital infrastructure to help reduce emissions. Chapter 4 examines the action needed to reduce emissions from the technology sector itself. Chapter 5 explores the interventions needed to support a data-enabled net zero economy. Chapter 6 brings together the areas for research and development identified in the study and sets out a collaborative mission to develop digital technology for the planet.

BOX 1

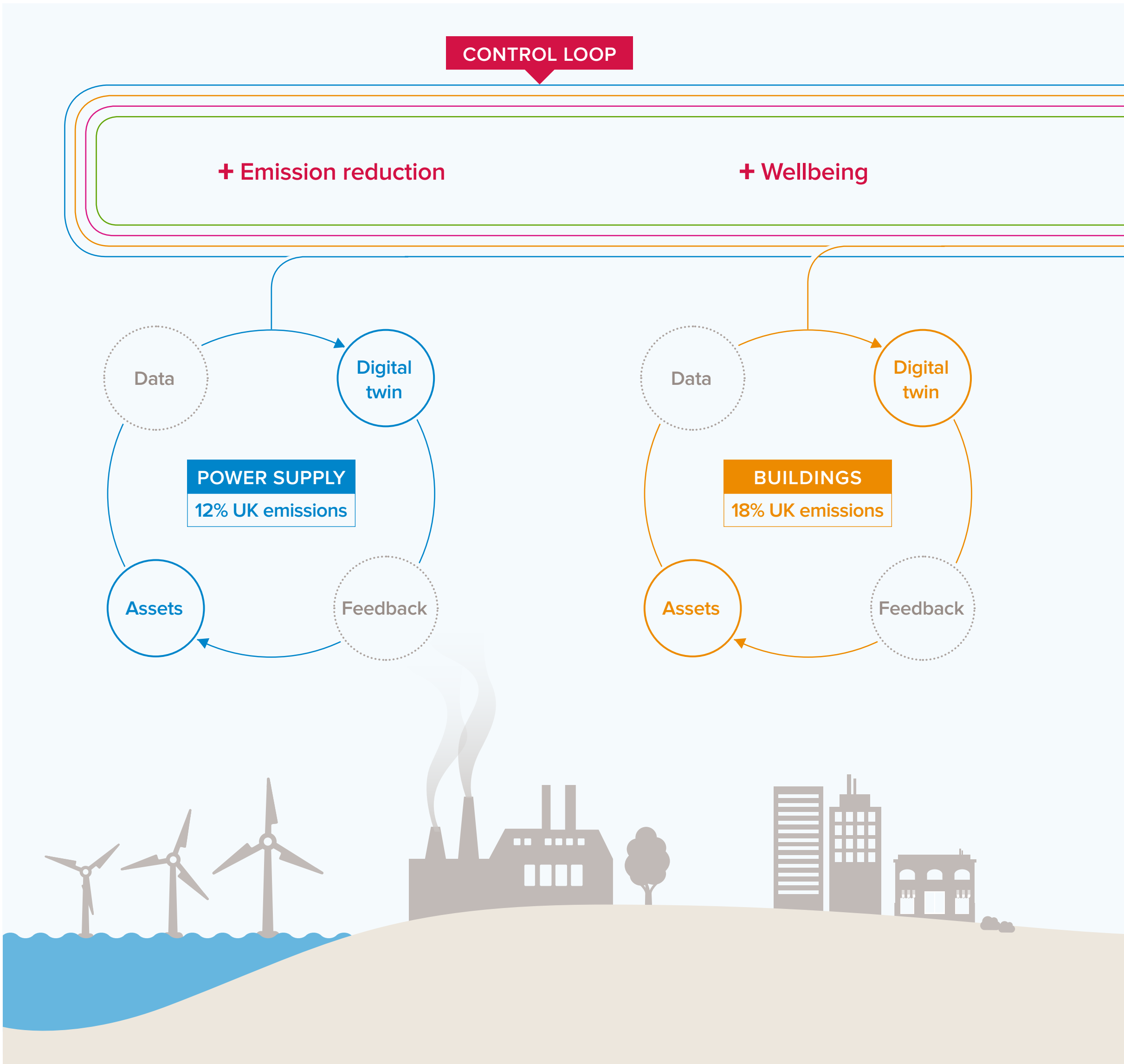
The digitalisation of the net zero transition.

The transition to a net zero economy and society requires urgent transformation across sectors, including the emergence of new services and in a number of cases the building of new infrastructure or the upgrading of existing ones. Data and digital technology have revolutionised communications and, under adequate policy conditions, they can catalyse the net zero transition across sectors in several ways, from planning to operation, and at different scales, from local to system level. The digitalisation of the net zero transition means a transition that involves collecting quality data on emissions and energy use and that uses that data to create innovative solutions and bring down energy use and emissions. A transition that makes the greatest use of digital technology and digital services to reduce energy use and emissions, in ways that serve all of society.

16. Montgomery J 2019 Tackling climate change with AI. The Royal Society blog. (see https://royalsociety.org/blog/2019/07/tackling-climate-change-with-ai/, accessed 14 October 2020)

FIGURE 1

In a future where every asset is connected through a digital infrastructure, it will be possible to establish 'control loops' enabling the monitoring, reduction and optimisation of greenhouse gas emissions across sectors. Such digital control loops will be defined by sensors collecting data, feeding into data-driven systems; these in turn will generate feedback which will be used to inform decisions and optimise these systems, taking into account multiple objectives such as emission reduction, biodiversity, resilience and wellbeing. Digital twins will be an essential part of such control loops (see Figure 2). Scaled across sectors and to a global level, this raises the possibility of a control loop for the planet, enabling a systems approach. The percentage of UK emissions indicated on the figure corresponds to the sector's share of 2019 UK emissions[17].



17. Climate Change Committee 2020 Reducing UK emissions, Progress Report to Parliament (see https://www.theccc.org.uk/publication/reducing-uk-emissions-2020-progress-report-to-parliament/, accessed 14 October 2020)

A better connected system with global optimisation would yield better overall solutions, beyond the local optima for each part of the system on its own. For example, reducing emissions from housing can be enabled by different combinations of reducing household energy consumption and of decarbonising energy supply. The establishment of control loops for the planet that work and are acceptable for everyone will require appropriate frameworks, in particular to ensure these digital systems are trustworthy, and to share data in a usable form, rapidly and safely.

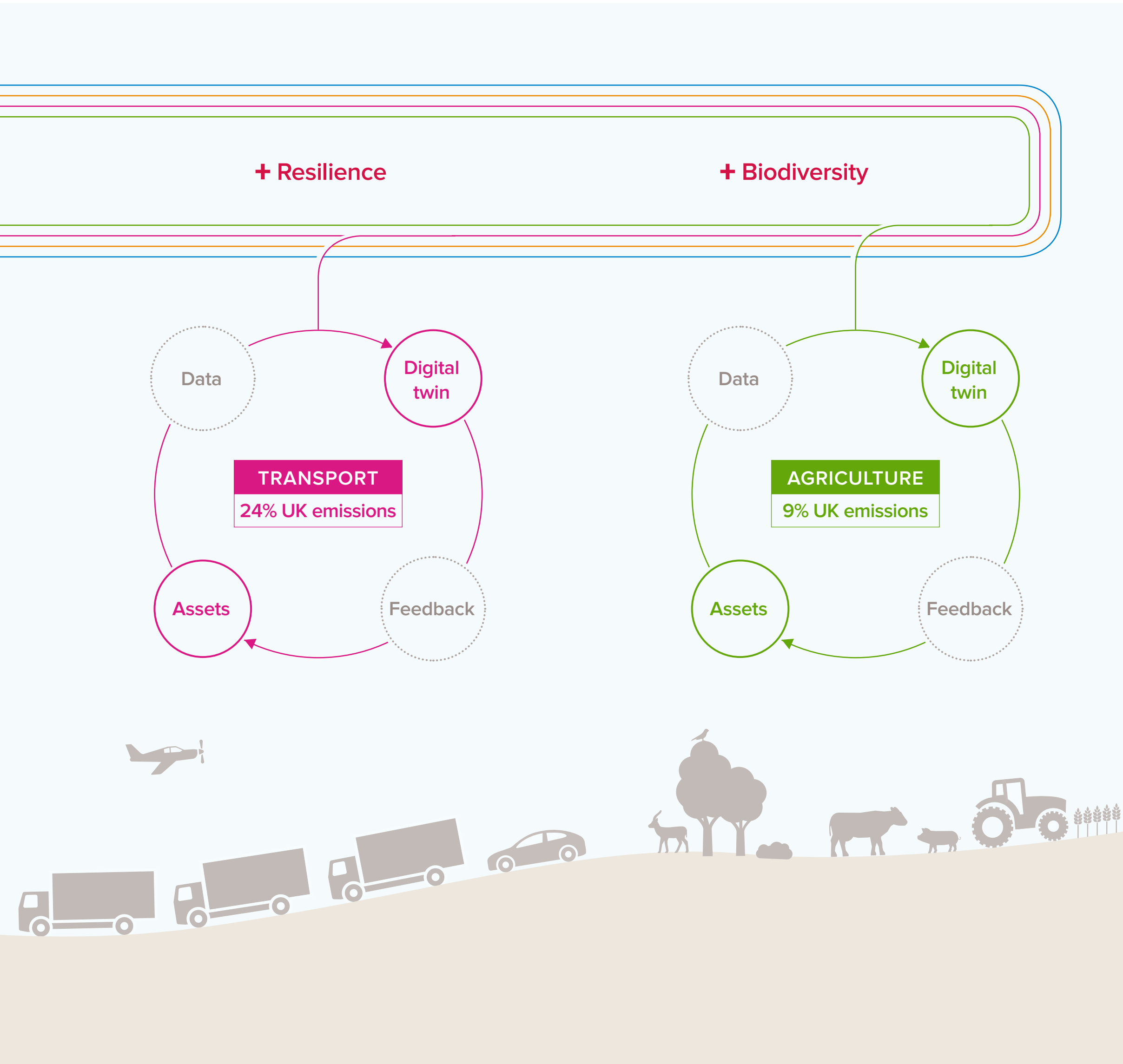
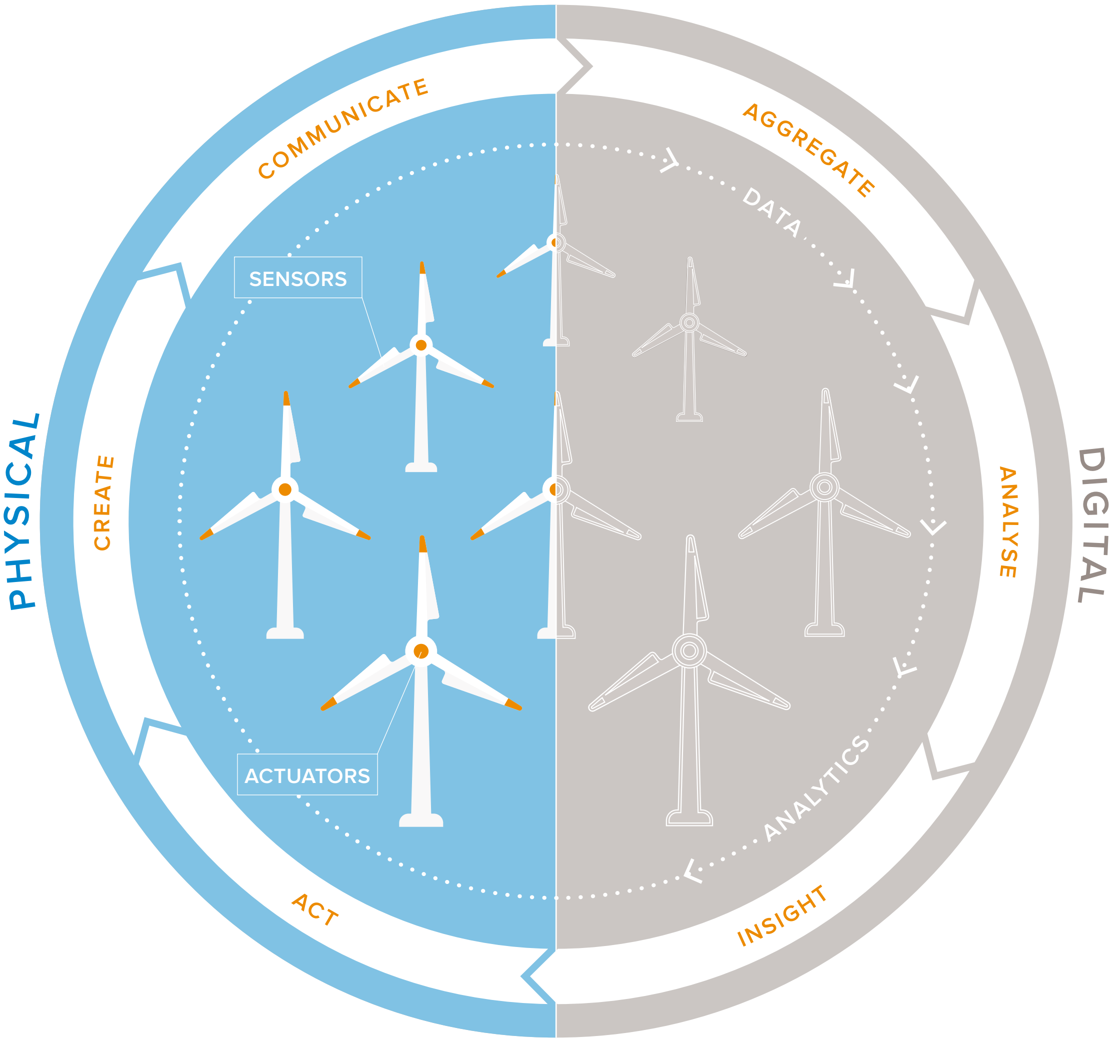


FIGURE 2

A digital twin is a virtual representation of a physical asset which can be used to understand, predict and optimise the performance of this asset. Simulations can be run before an asset is built or during its use, with then the possibility to feedback real-time data. This feedback loop enables a control loop, with the possibility to adjust the real-world set up based on insights from the simulation. Digital twins can also be used to carry out stress tests, and to explore the impact of new policies or interventions.



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Chapter one
Transforming the future

Left
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Transforming the future

Existing digital technologies could help cut 15% of UK emissions by 2030.

By collecting and analysing the vast amounts of data generated by daily activities, digital technologies offer opportunities to monitor, learn from, organise and optimise, or control processes in ways that significantly reduce emissions. From transport to manufacturing, and agriculture to energy, there are opportunities across sectors to deploy these technologies in support of net zero.

The potential of digital technology to support a low-carbon economy

From enabling remote working to supporting precision-farming, digital technologies can help a shift towards low-carbon ways of living and working. In so doing, digital technologies can also create wealth and jobs – for example a study considering AI alone estimated that the technology's environmental applications could save up to 4% greenhouse gas emissions by 2030, contribute up to $5.2 trillion USD to the global economy in 2030 and create 38.2 million net new jobs across the world[18]. Studies suggest that, taken together, digital technology already in the field could help reduce UK and global carbon emissions by up to 15%[19,20], contributing nearly a third of the 50% reduction required by 2030 in order to keep on a pathway to a global average temperature of well below 2°C. For example:

- The internet and videoconferencing services have enabled many to work from home during the COVID-19 pandemic. This corresponding reduction in travel contributed to a sharp drop in carbon emissions during lockdowns, with daily global fossil carbon emissions down 17% in early April 2020 compared with the previous year, and 2020 emissions overall were estimated to be down 4 to 7% compared to 2019 levels[21,22].
- Transport data being made open has supported the development of apps such as Citymapper, which allows access to information about traffic in real-time so individuals can choose less congested routes, thereby improving individual journeys as well as reducing congestion and emissions.
- The application of modelling has enabled more local, accurate weather forecast which has helped protect crops in fields, as well as made wind and solar renewable energy generation more predictable. Investment in supercomputing, in conjunction with machine learning and artificial intelligence, promise more advances and greater preparedness to weather disruption[23].
- Improved weather forecasting has also helped supermarkets stack their shelves with weather-appropriate food – contributing to a reduction in waste and therefore in emissions.

18. Microsoft and PwC UK 2019 How AI can enable a sustainable future (see https://www.pwc.co.uk/sustainability-climate-change/assets/pdf/how-ai-can-enable-a-sustainable-future.pdf, accessed 14 October 2020)
19. techUK 2020 Making the UK a digital clean tech leader (see https://www.techuk.org/resource/techuk-report-making-the-uk-a-digital-clean-tech-leader.html, accessed 25 November 2020)
20. Ekholm B and Rockström J 2019 Digital technology can cut global emissions by 15%. Here's how (see https://www.weforum.org/agenda/2019/01/why-digitalization-is-the-key-to-exponential-climate-action/, accessed 14 October 2020)
21. Le Quéré C *et al* 2020 Temporary reduction in daily global CO2 emissions during the COVID-19 forced confinement. Nat. Clim. Chang. 10, 647–653. (see https://doi.org/10.1038/s41558-020-0797-x, accessed 14 October 2020)
22. World Meteorological Association, UN Environment Programme, Global Carbon Project, Intergovernmental Panel on Climate Change, UNESCO, Met Office 2020 United in Science 2020: A multi-organization high-level compilation of the latest climate science information (see https://public.wmo.int/en/resources/united_in_science, accessed 14 October 2020)
23. Met Office 2020 Up to £1.2billion for weather and climate supercomputer (see https://www.metoffice.gov.uk/about-us/press-office/news/corporate/2020/supercomputer-funding-2020, accessed 14 October 2020)

- In agriculture, robotics and precision farming have helped optimise yields, contributing to food security whilst saving energy and reducing pressure on land.
- The application of digital twinning has enabled the real-time digital simulation of factories, which enables the optimisation of its operations as well as predictive maintenance, reducing downtime and thus saving energy and emissions. Digital technologies more broadly have an important role in maintaining and improving existing assets, which may have a lower carbon impact than building new.
- Virtual reality and augmented reality has enabled architects and users to digitally experience a space and modify plans before construction, thus saving time, money and emissions[24].

The sketches that follow explore how digital technologies could contribute to further emission reductions as well as greater monitoring of these emissions, in energy, transport, buildings, and environmental and resource management.

A future digitally-enabled net zero economy and society

Transforming energy supply and demand

Energy supply is one of the largest sources of emissions, amounting to a fifth of total emissions in the UK[25]. Electricity supply is also the sector which has achieved the biggest reductions in emissions in the UK over the past ten years[26]. Fossil fuels generated 75% of the country's electricity in 2010, but with the rapid disappearance of coal, this share has fallen to 43% in 2019, mainly coming from gas-powered electricity generation[27]. In the meantime, low-carbon generation reached a record high of more than half of total UK generation in 2018 and 2019, with renewables producing two thirds of this low-carbon generation and the rest coming from nuclear[28]. With half of the UK's nuclear power plants set to retire by 2025, renewables generation will need to increase rapidly in order to meet the UK's increasing electricity needs. This presents a challenge as the current main sources of renewable electricity (such as wind and solar energy) feed into energy networks only intermittently, meaning production risks not always matching demand if storage, interconnectors or other back-up power plant capacity are not developed.

24. Adrian Thompson 2019 Virtual and Augmented Reality for Construction (see https://www.buildings.com/news/industry-news/articleid/21978/title/virtual-augmented-reality-construction, accessed 14 October 2020)
25. Electricity supply generated 12% of UK emissions in 2019, and fossil fuel supply another 8% - upstream emissions from oil and gas production.
26. *Op. Cit.* 17
27. Evan S 2020 Analysis: UK low-carbon electricity generation stalls in 2019. Carbon Brief. (see https://www.carbonbrief.org/analysis-uk-low-carbon-electricity-generation-stalls-in-2019, accessed 14 October 2020)
28. *Op. Cit.* 17

Digital twins can increase wind farms' annual output by up to 20%.

By modelling the availability of different energy sources, and forecasting supply and demand across the system, technologies such as AI and digital twinning can help integrate intermittent renewable energy sources into the grid[29]. Already, digital twins are applied at the scale of wind farms (see Figure 2), improving operations, maintenance and reliability, and they could increase the wind farms' annual energy production by up to 20%[30,31]. Digital models of wind farms help optimise the design of wind turbines for each pad in the windfarm, based on the specific geography of the site – whether onshore or offshore. Once the turbines are in place, the digital twin helps monitor the wind farm's operation and maintenance needs remotely, and provides suggestions to make it even more efficient.

In addition to these new national sources of energy, new local sources of energy are also emerging, and such decentralised energy generation will be increasingly important to future energy systems[32]. For example, homes equipped with smart meters and fitted with clean energy sources, as well as newly developed energy storage, can plug into the grid and supply energy into distributed energy networks.

Smart meters could contribute a 25% emissions saving from UK homes by 2035 (compared with 2015 levels), by enabling a flexible, decentralised and decarbonised energy system[33]. Whilst plugged into the grid to charge, drawing from the grid, electric vehicles also store energy[34]. Vehicle-to-grid discharging can, in turn, help balance the grid. As these become more common, there will be more opportunities, in terms of distributed generation and storage increasing flexibility in the grid, as well as challenges in managing such a distributed system. In increasingly complex grid architectures, one of the challenges will be to still maintain the grid frequency at 50 Hz, and digital developments may help grid 'control loops' achieve this.

More digital technologies with applications in energy systems are likely to be developed in the near future. The International Energy Agency listed more than eighty technologies related to the digitalisation of energy, with a third of them still at the prototype or demonstration stage, and another third only in early adoption[35]. Data sharing and digitalisation in particular will be critical to the restructuring, planning and operation of future energy systems[36,37,38].

29. Arup 2019 Digital twin, towards a meaningful framework (see https://www.arup.com/-/media/arup/files/publications/d/digital-twin-report.pdf, accessed 14 October 2020)
30. Rook B 2019 How digital twins are transforming wind operations. Windpower Engineering & Development. (see https://www.windpowerengineering.com/how-digital-twins-are-transforming-wind-operations/, accessed 14 October 2020)
31. GE 2015 Wind in the Cloud? How the Digital Wind Farm Will Make Wind Power 20 Percent More Efficient (see https://www.ge.com/news/reports/wind-in-the-cloud-how-the-digital-wind-farm-will-2, accessed 14 October 2020)
32. National Grid ESO 2020 Future Energy Scenarios (see https://www.nationalgrideso.com/future-energy/future-energy-scenarios, accessed 14 October 2020)
33. Delta Energy & Environment 2019 Smart meter benefit: Role of smart meters in responding to climate change (see https://www.smartenergygb.org/en/resources/press-centre/press-releases-folder/delta-ee-carbon-savings, accessed 14 October 2020)
34. British Standards Institute 2018 Secure and interoperable use of smart appliances and electric vehicle smart charge points through standards (see https://www.bsigroup.com/en-GB/smart-appliances-flexible-energy/, accessed 14 October 2020)
35. International Energy Agency 2020 Clean Energy Innovation. Energy Technology Perspectives. (see https://www.iea.org/reports/clean-energy-innovation, accessed 14 October 2020)
36. Energy Systems Catapult 2020 Digitalisation for Net Zero (see https://es.catapult.org.uk/reports/digitalisation-for-net-zero/?download=true, accessed 14 October 2020)
37. *Op. Cit.* 32
38. Imperial College London 2020 Digitalisation of Energy, An Energy Futures Lab Briefing Paper (see https://www.imperial.ac.uk/energy-futures-lab/policy/briefing-papers/paper-5/, accessed 14 October 2020)

The Climate Change Committee estimated that without a flexible energy system, which smart meters and digital technology are a key part of unlocking, the costs of delivering net zero emissions by 2050 could be up to £16bn per annum higher[39]. It is estimated that only about 2% of the demand side flexibility that could be enabled by digital technology is currently being exploited[40]. Building energy management systems can help realise the largest share of this potential, for example by scheduling electric appliances to run at times of peak renewable energy production. Similarly, some data centres have scheduled computing jobs to maximise the use of intermittent renewables, and therefore contribute to uptake of clean energy and to demand side flexibility – a substantial proportion of computing jobs lend themselves to such scheduling[41].

In the longer-term, digital technology could further help enable different types of low-carbon energy sources. Machine learning techniques can support innovation in low-carbon fuels and energy storage[42]. Computer models have been used to help synthesize, characterize, model, and design materials. In addition, digital twinning can help run simulations of future energy systems, exploring for example the extent to which hydrogen or other low-carbon fuels[43] will be a substantial part of the energy mix. Such simulations would then inform the planning of future systems and help improve efficiency as well as resilience.

Enabling clean mobility

Transport is the biggest emitting sector in the UK, accounting for 24% of 2019's emissions, and is a sector where there are already many applications of digital technology that can support emission reductions from transport. For example, machine learning is being applied to understand how vehicles are moving around city centres, and in places has helped improve congestion prediction by 50% compared with traditional modelling approaches[44]. Smart parking has been piloted, deploying sensors in parking spaces and communicating the information to road users through apps, with the potential to halve congestion in busy city areas[45]. In both cases, the information can be used to ease traffic, as well as reduce emissions.

Computer techniques make it possible to optimise the use of existing physical infrastructure, in multiple ways. Business and operating models that offer 'mobility as a service' can leverage digital technologies to support more fundamental changes to how individuals access transport services, reducing the number of personal vehicles on the roads. Data-enabled transport service platforms can enable users to access, pay for, and get real-time information on, a range of transport options with the aim of promoting use of public transport and making it easy for individuals to complete their journeys using low carbon modes of transport[46].

Digital twinning can simulate how hydrogen and low-carbon fuels will transform future energy systems.

39. Imperial College London 2018 Analysis of Alternative UK Heat Decarbonisation Pathways, for the Committee on Climate Change (see https://www.theccc.org.uk/wp-content/uploads/2018/06/Imperial-College-2018-Analysis-of-Alternative-UK-Heat-Decarbonisation-Pathways.pdf, accessed 14 October 2020)

40. *Op. Cit.* 35

41. Radovanovic A 2020 Our data centers now work harder when the sun shines and wind blows (see https://blog.google/inside-google/infrastructure/data-centers-work-harder-sun-shines-wind-blows, accessed 14 October 2020)

42. Rolnick *et al* 2019 Tackling climate change with machine learning. arXiv:1906.05433 (see https://arxiv.org/pdf/1906.05433.pdf, accessed 14 October 2020)

43. The Royal Society 2017 Low carbon energy programme (see https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/, accessed 14 October 2020)

44. *Op. cit.* 12

45. BT 2016 Saving money and reducing emissions in Milton Keynes using smart parking (see https://www.iot.bt.com/assets/documents/bt-milton-keynes-innovative-parking-case-study.pdf, accessed 14 October 2020)

46. Government Office for Science 2018 Mobility as a Service (MaaS) in the UK: change and its implications (see https://www.gov.uk/government/publications/future-of-mobility-mobility-as-a-service, accessed 14 October 2020)

Digital technology allows the optimisation of routes and travel times, avoiding empty delivery vans and duplicate journeys.

Other approaches will help reduce travel and its emissions altogether. Building on developments in videoconferencing and their rapid uptake to enable virtual meetings during the COVID-19 pandemic, further improvements in creating a sense of 'virtual presence', perhaps underpinned by immersive technologies, could spur a lasting reduction in business travel.

In logistics, digital technology can help consolidate demand and facilitate collaboration between delivery and logistics providers. This allows the identification of the most sensible routes and travel times, avoiding empty vans and duplicate journeys. Such changes can be stimulated by the benefits they offer in terms of cost reduction, accelerated delivery timeframes and a better end-user experience.

The logistics sector might also save emissions by taking up autonomous vehicles[47]. The machine learning algorithms operating the driverless vehicles can be designed to learn and optimise routes and driving conditions. It would also make it possible to run aerodynamic convoys of autonomous freight vehicles on motorways overnight, and thus reduce congestion and emissions. Such vehicles will rely on the development of safe and robust AI systems, enabling them to navigate their environments autonomously. As automation becomes increasingly pervasive, there may be implications for the skills and composition of the sector's workforce.

Understand and support low-carbon, sustainable individual behaviours

A switch to low-carbon, sustainable behaviours and practice will be pivotal in achieving a net zero economy and society[48]. To support this, data analytics and digital technologies can be used to understand and encourage changes in individual behaviours.

Currently, around 40% of the UK's total emissions come from households, and heating is the biggest contributor to household emissions[49]. Smart meters are already deployed in many UK homes and the data they collect offers insight into electricity and gas consumption patterns. At present, this information is used to ensure energy bills automatically reflect consumption, or to help suppliers forecast energy usage and better manage supply and demand. Smart home technologies have the potential to support changes in behaviours and significant emission reductions, for example by identifying how to improve home infrastructures.

Consumer research shows that smart heating controls give users a greater sense of control over their heating, meaning they can adjust their heating to suit their daily routine, heat selective rooms rather than the whole home, and heat rooms to different temperatures, for instance to make different occupants feel comfortable[50]. For people to engage effectively with this technology, it will need to present actionable information through clear and engaging user interfaces.

47. The Royal Society 2020 Digital technologies and the planet, Note of discussions at a Royal Society workshop (see https://royalsociety.org/-/media/policy/projects/digital-technology-and-the-planet/digital-technology-and-the-planet-summary-notes.pdf, accessed 14 October 2020)
48. Imperial College London 2019 Behaviour change, public engagement and Net Zero, A report for the Committee on Climate Change (see https://www.theccc.org.uk/wp-content/uploads/2019/10/Behaviour-change-public-engagement-and-Net-Zero-Imperial-College-London.pdf, accessed 14 October 2020)
49. Climate Change Committee 2016 The Fifth Carbon Budget, How every household can help reduce the UK's carbon footprint (see https://www.theccc.org.uk/wp-content/uploads/2016/07/5CB-Infographic-FINAL-.pdf, accessed 14 October 2020)
50. Energy Systems Catapult and Department for Business Energy and Industrial Strategy 2020 Using the Living Lab to sell consumer centric heat services that encourage adoption of low carbon heating (see https://es.catapult.org.uk/reports/using-the-living-lab-to-sell-consumer-centric-heat-services-that-encourage-adoption-of-low-carbon-heating/?download=true, accessed 14 October 2020)

Further examples of applications of digital technology to support low-carbon behaviours include platforms to enable the sharing and re-use of goods, such as the trading of second-hand clothes[51]. While digital technology could bolster online retail and unsustainable levels of consumption (see Box 2), the fashion resale market is trending upwards and there is evidence that it has grown even further during the COVID-19 pandemic[52].

Platforms enabled by mobility data can support personal carbon trading and apps that enable citizens to track and visualise in real-time their mobility carbon footprint[53]. In future, apps will integrate multiple sources of data and provide intuitive dashboards and visual tools for individuals to track their emissions and gain insight into the impact of their food choices, shopping and travel habits.

Optimising resource use through building management and materials re-use

Reducing waste across the board should be priority in achieving net zero. Digital technologies offer opportunities to optimise patterns of resource use, by enabling better construction and building management, as well as materials re-use.

Intelligent building management systems that combine data about the energy use of buildings and other information sources like weather data, to recommend the most sensible heating and cooling patterns, are already available to managers of commercial buildings to reduce energy use and emissions[54].

Energy loss from existing buildings could be greatly reduced by renovations that add insulation alongside a technological retrofit – combining sensors, technologies such as heat pumps and energy management systems to control energy use while prioritising clean energy. Such combinations would be cheaper than renovating buildings to the highest insulation standard (found for example in 'Passive Houses'), as well as provide control and wellbeing. This approach can enable reductions in energy use and create a better environment for inhabitants, ensuring more comfortable temperatures both in winter and in summer.

In practice, the existing building stock is very diverse and will require a wide range of interventions. The Greater London Authority has started using a digital twin to monitor, simulate and analyse the whole city's building stock[55].

Renovations and technological retrofit can enable reductions in home energy use and create a better environment for inhabitants.

51. Young S 2020 5 best second hand fashion apps to use during second hand September and beyond. The Independent. (see https://www.independent.co.uk/life-style/fashion/second-hand-september-vintage-preloved-fashion-apps-depop-vestiare-vinted-ebay-a9093361.html, accessed 14 October 2020)
52. Segarra M 2020 Secondhand clothing sales are growing during the pandemic (see https://www.marketplace.org/2020/07/01/secondhand-clothing-sales-are-growing-during-the-pandemic/, accessed 14 October 2020)
53. City of Lahti 2020 CitiCAP project: Promoting sustainable urban mobility in Lahti (see https://www.lahti.fi/en/services/transportation-and-streets/citicap, accessed 14 October 2020)
54. International Energy Agency 2019 Case Study: Artificial Intelligence for Building Energy Management Systems (see https://www.iea.org/articles/case-study-artificial-intelligence-for-building-energy-management-systems, accessed 14 October 2020)
55. Steadman P *et al* 2020 Building stock energy modelling in the UK: the 3DStock method and the London Building Stock Model. Buildings and Cities, 1(1), 100–119. (see https://journal-buildingscities.org/articles/10.5334/bc.52/, accessed 14 October 2020)

Digital technology can support the circular economy by making it possible to identify, track and trade materials for re-use.

This can help target interventions depending on built form, age, activity, energy performance, and enables linking with confidential socioeconomic data on occupants. Data and digital technology can also inform the planning and development of new buildings. The sharing of information about buildings' energy performance in their use phase, and the track record of different materials, would enable the construction industry to generate better models and design more efficient buildings.

Digital technologies also offer opportunities to make more effective use of resources across a range of daily activities. A switch to a circular economy, an economic model focused on reuse and eliminating waste, is a tenet of sustainability and would also achieve considerable emission reductions. Digital technology can support the circular economy by making it possible to identify, track and trade materials for re-use. Sensors can generate data across the lifecycle of products and digital immutable records could help keep a log of the materials and emissions history of a product. By helping identify and match manufacturers in need of resources with those that can provide such resources, these technologies help reduce the volume of material currently disregarded as waste, creating 'industrial symbiosis' – mutually beneficial relationships between business. Already, pilot 'foraging factories' sense emerging waste from people's homes, farms and other facilities and find opportunities to reuse it[56].

The circular economy would also help address concerns that the production of digital systems relies on finite sources of rare materials, the mining of which usually results in significant environmental costs[57]. The tracking of rare materials will be critical to their effective use and re-use and to ensure their availability for instance to manufacture mobile phones or solar panels.

Removing greenhouse gas from the atmosphere

In some sectors, notably agriculture and aviation, greenhouse gas emissions will be difficult to eliminate entirely, so we will need technologies to compensate by removing greenhouse gases from the atmosphere[58]. As well as helping achieve emission reductions across sectors, machine learning also has potential to help nature-based climate mitigation measures and engineering-based solutions to remove greenhouse gas from the atmosphere[59]. Machine learning, in conjunction with drones and other smart machines, can be employed to automate large-scale tree-planting, locating appropriate sites and planting seeds more quickly and cheaply than traditional methods. Machine learning can be used to monitor carbon stock, and, together with eg remote sensing, it can be used to map peatlands, and assist in protecting them from drought and fires (avoiding the release of large amounts of carbon into the atmosphere). Additionally, data-driven research and development in direct air capture and sequestration could help scientists discover carbon dioxide sorbents with improved properties.

56. University of Cambridge 2017 Factories that forage (see https://www.cam.ac.uk/news/factories-that-forage, accessed 14 October 2020)
57. Charalampides G *et al* 2016 Environmental Defects And Economic Impact On Global Market Of Rare Earth Metals. IOP Conf. Ser.: Mater. Sci. Eng. 161 012069 (see https://iopscience.iop.org/article/10.1088/1757-899X/161/1/012069/pdf, accessed 14 October 2020)
58. The Royal Society and The Royal Academy of Engineering 2018 Greenhouse has removal (see https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf, accessed 14 October 2020)
59. *Op. Cit.* 42

Integrating Sustainable Development Goals

Beyond emissions reduction, there is an opportunity to use digital technology to optimise systems for multiple environmental and societal goals. Several Sustainable Development Goals (SDGs) are related to the potential benefits of applications of digital technologies for net zero, in particular: SDG2 'Zero hunger', SDG 6 'Clean water and sanitation', SDG 7 'affordable and clean energy', SDG 10 'Reduce inequalities', SDG 11 'Sustainable cities and communities', SDG 12 'Responsible consumption and production', SDG 13 'Climate action, and SDG15 'Life on land' which includes the reversal of biodiversity loss.

Optimisation for one goal can have adverse effects on another, and digital technologies can allow a systems approach, bringing a better understanding of such interactions and thus better integrated interventions[60]. This can build on ongoing national and international efforts to define indicators for each SDG and to use data and AI both to achieve and to monitor progress[61].

Building accountability in the system

Achieving net zero will require an ability to effectively monitor and control emissions from different parts of the system. This will help enforce regulations such as carbon pricing. Currently, many organisations in the UK are required to report their energy use and greenhouse gas emissions on an annual basis[62]. However, for many of these organisations there is no obligation to report emissions occurring upstream in the supply chain (part of Scope 3 emissions)[63]. Tracing all emissions along complex, global supply chains, will be necessary in order to have a complete understanding of the manufacturing system and hold different parties accountable for their emissions. Digital technology offers ways to address this complexity: networks of sensors can collect accurate data on energy use from industrial machinery[64], and emerging technologies can support transparency and verifiability of these measurements[65], so organisations and consumers better understand the emissions produced in manufacturing and transport of goods.

60. The Royal Academy of Engineering 2020 Net Zero: A systems perspective on the climate challenge (see raeng.org.uk/publications/reports/net-zero-a-systems-perspective-on-the-climate-chal, accessed 14 October 2020)

61. See https://www.un.org/en/sections/issues-depth/big-data-sustainable-development/index.html, accessed 14 October 2020

62. Carbon Trust 2020 SECR explained: Streamlined Energy & Carbon Reporting framework for UK business (see https://www.carbontrust.com/news-and-events/insights/secr-explained-streamlined-energy-carbon-reporting-framework-for-uk, accessed 14 October 2020)

63. As defined in the Kyoto Protocol, Scope 1 emissions correspond to direct greenhouse gas emissions from sources owned or controlled by an organisation; Scope 2 indicates indirect emissions associated with the production of electricity, heat, or steam purchased by the reporting entity; Scope 3 indicates all other indirect emissions, for example emissions associated with the extraction and production of purchased materials, fuels, and services, including transport in vehicles not owned or controlled by the reporting entity, outsourced activities, waste disposal, etc.
For more detail: World Business Council on Sustainable Development (WBCSD) and World Resources Institute (WRI) 2004 The Greenhouse Gas Protocol - A Corporate Accounting and Reporting Standard. Geneva and Washington, DC. (see https://www.wri.org/publication/greenhouse-gas-protocol, accessed 14 October 2020)

64. Incipini L *et al* 2019 IoT Network for Industrial Machine Energy Monitoring. 2019 AEIT International Annual Conference (AEIT), Florence, Italy, pp. 1-6. (see https://ieeexplore.ieee.org/document/8893312, accessed 14 October 2020)

65. Kemp L 2020 Climate-conscious tech can mobilise diamond sustainability (see https://www.everledger.io/climate-conscious-tech-can-mobilise-diamond-sustainability/, accessed 14 October 2020)

Digital technology can make food systems more resilient, increasing yields, reducing waste and improving adaptability to a changing climate.

If they can be scaled while limiting their carbon footprint, blockchain-style technologies[66] could be among the technologies enabling emissions and materials traceability, to know when, where and how many emissions and materials are being generated and used across a supply chain (see Box 3)[67]. Such technologies also provide transparency and verifiability by creating immutable copies of records across the system, so different users can access accurate information about emissions generated in production.

Digital technologies also offer the possibility of observing, modelling, monitoring and verifying the use of land and its greenhouse gas emissions and storage. Systems of data collection and reporting could underpin mechanisms that encourage parties involved in land management to be held accountable for emissions from different sources. Accessible apps available on everyday devices can support the widest uptake of models for soil management or monitoring purposes[68].

Embedding resilience

Resilience relates to the ability of systems to adapt to crises and to deal with situations putting the system under strain. Climate change is expected to create a whole range of changes that will test the resilience of systems humankind relies on, with extreme weather damaging infrastructure, altering ecosystems and endangering species, as well as exacerbating water scarcity and flood risks[69].

Digital technologies offer the opportunity to support the resilience of land management systems by predicting emerging weather patterns and informing adaptation based on data from other regions of the globe.

The COVID-19 pandemic has revealed how global, 'just-in-time' supply chains could suffer from events limiting trade around the globe. This illustrates a challenge in achieving both efficiency and resilience[70]: reducing stocks can make supply chains vulnerable if part of the supply is interrupted or if demand slightly increases. The optimisation of supply chains enabled by AI and other algorithms should account for this, for example by identifying critical supply chains and protecting a buffer inventory in parts of the supply chain that are most at risk of being disrupted. Additive manufacturing could support just-in-time manufacturing closer to the point of consumption, reducing the logistics footprint and waste, as well as enabling greater personalisation.

In agriculture, the combination of modelling and forecasting together with engaging user-interfaces available on mobile phones could help every farmer around the world make both short-term decisions e.g. about harvest timings, and longer-term decisions about crop choice and land management. This can enable much more joined-up and resilient food systems, increasing yields, reducing waste and improving adaptability to a changing climate.

66. Blockchain is an open, distributed ledger that can record transactions between several parties efficiently and in a verifiable and permanent way. Note that there are different forms of blockchain, and some have a higher carbon footprint than others (see Chapter 4).

67. *Op. Cit.* 65

68. The Royal Society 2020 Soil structure and its benefits: An evidence synthesis (see https://royalsociety.org/-/media/policy/projects/soil-structures/soil-structure-evidence-synthesis-report.pdf, accessed 15 October 2020)

69. The Royal Society 2014 Resilience to extreme weather (see https://royalsociety.org/topics-policy/projects/resilience-extreme-weather/, accessed 15 October 2020)

70. McKinnon A 2018 Balancing Efficiency and Resilience in Multimodal Supply Chains, International Transport Forum Discussion Papers, OECD Publishing, Paris. (see https://www.itf-oecd.org/sites/default/files/docs/efficiency-resilience-multimodal-supply-chains_0.pdf, accessed 15 October 2020)

Building a digital twin of the food system will be instrumental in understanding the externalities of different farming practice at scale, and their impact on systemic resilience. The externalities of conventional agriculture can include flood risk, pollution and public health issues. Digital twins could help test the implications of new practice deployed on a very large scale, such as vertical farming, where automated water circuits feed crops and robots nurture and harvest them[71]. Vertical farming offer the possibility to grow food closer to the consumer, at a fraction of the water consumption, with reduced transport and waste, no pesticides and no soil erosion.

Digital technologies for the planet

A control loop for the planet

As illustrated above, many applications of digital technologies will help multiple sectors achieve net zero. In combination, data-driven systems can connect, generate and exchange data and feedback. In effect, they can constitute 'control loops' that underpin systems-approaches to inform decisions and enable the optimisation of systems to reduce emissions. Scaled to global level, this raises the possibility of a control loop for the planet. This would act as a master version of digital twinning, joining up all sectoral systems and enabling the control and optimisation of the operation and output from the whole system – in other words a planetary digital twin.

Energy systems can build on existing uses of AI and digital twinning to achieve such a control loop. Orchestrating digital twins of assets across the UK's energy system would further improve the planning, operations, maintenance and resilience of the grid as a whole. Similarly connecting digital twins and emissions data records from factories and logistics along a supply chain would allow the better planning and running of the infrastructure. Importantly, system-wide control loops would bring a greater understanding of ways to reduce and optimise emissions across systems. As digital systems will control the running of critical infrastructure such as food and energy supply chains, they will need to be trustworthy and resilient. The data-driven systems underpinning these control loops constitute critical digital infrastructure.

Interdependencies in the system will need to be considered, as interventions in one area might lead to rebound effects in another. For example, increased working from home, enabled by the internet and videoconferencing, might reduce the need to travel to work as much, but it might mean that people then choose to live further away from their workplace and other amenities, and hence travel further by car – and thus lead to a rebound in emissions[72]. In many cases, the emission savings may justify the cost of building new, data-enabled infrastructure. However, the introduction of new infrastructure and technologies, such as blockchain in distributed energy systems or to track goods and their emissions, could also lead to rebound effects (also see dystopian scenarios described in Box 2). This speaks to the critical need to model and monitor the impact of new infrastructures, policies and interventions, which digital twinning makes possible.

Interdependencies in the system must be considered, as interventions in one area might lead to rebound effects in another.

71. Thompson A 2020 Indoor Vertical Farm In Cincinnati Will Be Fully Automated (see https://www.npr.org/2020/01/29/800725833/indoor-vertical-farm-in-cincinnati-will-be-fully-automated?t=1597409074665, accessed 15 October 2020)

72. Hook A *et al* 2020 A systematic review of the energy and climate impacts of teleworking. Environ. Res. Lett. 15 093003 (see https://iopscience.iop.org/article/10.1088/1748-9326/ab8a84, accessed 15 October 2020)

BOX 2

Dystopian scenarios: Digital technology against the planet

Digital technology is a tool that can be used in different ways and there are potential scenarios that should be recognised, where digital technology creates a rise in emissions.

Data-driven unsustainable behaviours

Digital technologies have rapidly changed economies and societies, and this trend is likely to continue, not least because everything in the world will have a digital representation. The manufacturing and retail industry could continue to use the internet and AI to enable fully automated, cheaper production and faster deliveries, offering a seamless experience to customers and bolstering consumption. The energy sector could further employ digital technology to pursue fossil-fuel extraction, thus maximising the use of this finite resource. Automation and precision farming could go on maximising yields and reducing costs, bringing ever cheaper products to consumers and trivialising waste. As a result, emissions would continue to rise.

Sensing beyond sense

In future, sensors could be everywhere, monitoring the emissions of everything. This might start from a good intention: enabling comprehensive monitoring of emissions in order to understand what can drive them down, and to act on this. But this could go too far. Year after year, Internet of Things devices with new capabilities could be deployed, generating a breadth of data. On the one hand, the more granular analyses that would become possible could, somewhat disappointingly, reveal that finer monitoring and controls of emissions yield only small reductions in overall emissions. On the other hand, the swarm of devices could add layers of embodied emissions and material waste into the environment, and the processing and storage of the vast amount of data they generate might come with a cost in emissions too – not to mention the fact that many people might feel oppressed by what they perceive as unnecessary pervasive surveillance. Could this future be avoided, with better use of available data sources, maintenance and upgrade of existing infrastructure, from ground sensors to satellites?

Core digital capabilities

The creation of such a control loop for the planet will depend on cross-cutting, core digital capabilities (also see Figure 3, and Box 3):

- **Model, optimise and predict:** Machine learning and AI for modelling and forecasting will underpin much of the data-driven transformation across sectors – as exemplified by applications to weather simulation – enabling decision-making, digital twinning (together with sensors), and system integration. This enables a wide range of technological developments from supply chain optimisations to autonomous vehicles.
- **Integrate, analyse and map data:** Data integration tools will need to combine data from multiple sources and of variable quality, and present actionable information through compelling user interfaces. Semantic maps can capture the topology and context (eg through knowledge graphs) in which the digital twins and control loops will operate, enabling collaborations and coordination. Automation also has a role in abstracting the complexity of data and digital technologies from the user.
- **Simulate (digital twinning)**: Digital twins deployed on a local level (such as smart homes) will be fed into whole-system modelling and twinning. Home energy management systems and smart home technologies are core to reducing heat loss from buildings, and they will also enable further transformations such as optimising homes for comfort and wellbeing, or distributed energy networks.
- **Sense, connect and actuate:** Hyper-connectivity will support fast communication in complex distributed systems, with the number of IoT sensors and devices set to increase. Such connectivity will make it possible to better connect digital twins with their physical counterparts, reconfiguring a physical system in real time, based on a digital simulation. Building interoperability into the software of connected devices will be essential.
- **Track and verify:** Tamper-proof records, supported by distributed or centralised ledgers[73], will be important for the accurate tracking and traceability of materials and emissions, to guarantee provenance, and ultimately to enable accountability across the system. This capability will need to build in robust security and privacy.

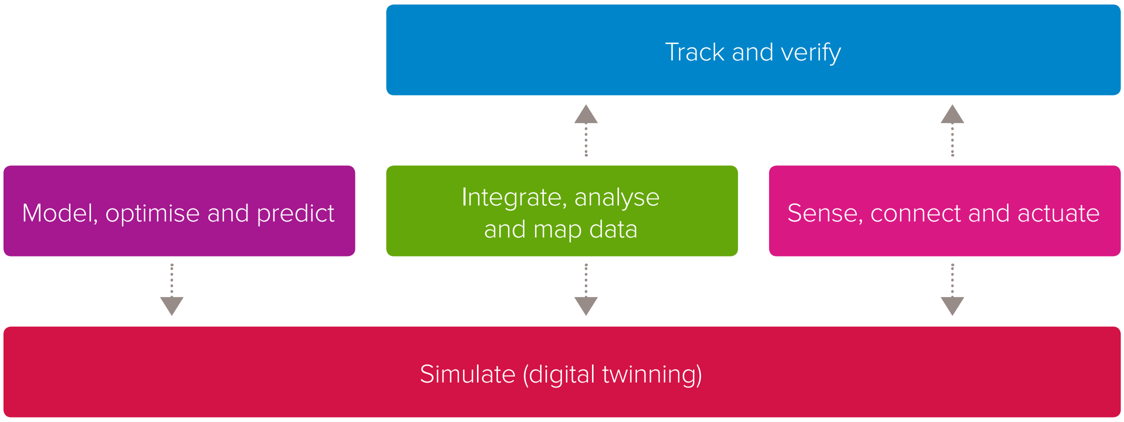
New technological capabilities will also require new skills, from basic digital literacy to make the most out of a smart meter at home, to advanced engineering and data science skills to build and optimally operate digital twins. For instance, to secure its decarbonisation through digitalisation, the energy sector needs both managers and technical experts combining knowledge and skills in energy, engineering and data[74].

73. Energy Futures Lab 2019 Energy and Blockchain: Is the future distributed ledgers and smart contracts? (see https://energyfutureslab.blog/2019/09/04/energy-and-blockchain-is-the-future-distributed-ledgers-and-smart-contracts/, accessed 15 October 2020)

74. Energy Systems Catapult, Department for Business, Energy and Industrial Strategy, Ofgem, Innovate UK 2019 A Strategy for a Modern Digitalised Energy System: Energy Data Taskforce report (see https://es.catapult.org.uk/reports/energy-data-taskforce-report/, accessed 15 October 2020)

FIGURE 3

The control loop of the planet will rely on several core digital capabilities. The ability to model, optimise and predict, combined with the ability to integrate and analyse data, and to connect, together enable digital twinning. Connectivity will also help collect data from sensors, which, together with the ability to analyse and visualise data, will support the ability to track and verify emissions through the system.



BOX 3

Core digital capabilities for net zero applied in practice.

Model, optimise and predict: The technologies underpinning this digital capability are mature, with applications deployed in a number of sectors, from reducing food waste through better forecasting, to regulating road traffic. Some applications require particularly high levels of robustness, such as safety critical AI for autonomous vehicles or for real-time optimisation of energy supply, and storage, in smart grids. Ongoing research and development efforts to address this include improving the interface between recommender systems and human operators.

Integrate, analyse and map data: Apps and user interfaces already help people navigate complex data, and semantic maps and knowledge graphs will be essential to operate digital twins. There are commercial apps to help farmers use a range of data, including from satellites, thereby enabling precision farming[75]. However, such technology is not widely used yet, and more needs to be done to improve data integration tools and make data-driven approaches more accessible to a broader base. Data quality varies from one dataset to another and data integration tools will need to handle this effectively and make it easy for users to combine multiple sources of data.

Simulate (digital twinning): Applications of digital twins to enable control loops for net zero are still in their early days. Applications for wind farms are emerging and promise to increase power generation by up to 20%. Digital twins have the potential to enable smart grids, buildings, and other assets, that would then be connected together in a control loop for the planet. More case studies will be needed to quantify the impact digital twinning can have on emissions.

Sense, connect and actuate: To some extent this core digital capability is available, as illustrated with the expansion of IoT devices, plus 4G and 5G networks. Other developments include edge computing where computation and storage happen closer to the location where they are needed. The critical digital infrastructure for the planet, such as smart grids, will rely on high connectivity and require reliable communication networks. Further technical improvements will be necessary.

Track and verify: This could rely on a range of technologies, including potentially certain forms of blockchain. There are early applications of blockchains to the traceability of materials along supply chain[76]. There is a need for good real-world case studies of energy-efficient blockchain-style technologies, or alternative approaches, for monitoring emissions across supply chains.

75. See https://ag-space.com/ (accessed 15 October 2020)

76. *Op. Cit.* 65

Creating policy frameworks to support the use of digital technologies for net zero

While enabling low-carbon innovation across sectors, these new uses of data also pose new dilemmas for society to navigate.

The desire to collect data and concerns about privacy or surveillance: Core to the development and deployment of digital technologies is access to data – about transport habits, energy use, consumption patterns, and more. As data is collected from a wider range of sources and as the capability to link data increases, granular insights can be generated into individual habits. The need to collect and use data will need to be balanced with concerns about privacy or surveillance. Making data available for net zero will bring shared benefits, but there could also be harms to individuals such as the undesired exposure of their travel or consumption habits. This will play out differently in different contexts: for example, real-time data from smart meters could leak information a user might want to remain private such as behavioural patterns deduced from patterns of appliance use; real-time data about business activity could raise concerns of surveillance in the workplace or reveal commercially sensitive information. Such trade-offs need to be managed in order to enable the use of data to develop digital applications for net zero.

Centralised and decentralised approaches to data management and technology development: Many of the technology applications that could enable a system-level change in activity – with resulting emission reductions – require data sharing or collaborations across organisations or stakeholders. This implies a centralisation of efforts to analyse data. Such centralisation facilitates data access for processing, but also creates risks, for example, potentially attracting cyberattacks. In addition, they presuppose that data subjects accept that a central trusted authority is in control of the data, which would need to be checked through public dialogue. Decentralised approaches, for example where processing happens on local devices ('edge computing'), might raise fewer privacy concerns, but they might require investment in new technology and a costly reshaping of existing infrastructure. The analysis of smart meter data is well suited for a decentralised approach, as smart meters could process detailed data locally and only share less granular, derivative insights of relevance to grid management. Such trade-offs will need to be thought through when designing data infrastructures and data-enabled applications.

Generating value from data for individuals and society: With growing interest in how companies can extract value from their data, there is increasing interest in how data can be treated as a valuable asset. However, data acquires value from use, which often requires structures to enable access and sharing across stakeholders, in order to combine or analyse data from different sources. There is a tension between the drivers to create value from data for individuals or organisations, and those to share data to benefit all. For example, farmers can be wary of sharing data with the entire supply chain, for fear that downstream organisations might enjoy greater financial benefits from farm-level data sharing than farmers themselves. Such trade-offs need to be managed in order to create a favourable environment for data access and enable the development of data-enabled technologies.

The chapters that follow explore the policy frameworks that can help negotiate these dilemmas.

Image © janiecbros.

Chapter two
Data infrastructures for net zero

Left
© FrankRamspott.

Data infrastructures for net zero

The development of data-driven technologies for net zero will require well-governed access to data.

In a future where every network of assets has a digital representation, the scale and variety of data types that are available to use will create a data environment that is fundamentally different to today. Data about energy use and emissions can be used to monitor and control emissions, enable carbon footprinting, or study trends in climate science or sustainability. Data about processes and behaviours from across sectors – from the mapping of physical assets to understanding consumer behaviour – could enable the development of digital technologies to reduce, optimise and control emissions.

The development of data-driven technologies for net zero will require well-governed access to such data, standards for data quality, interoperable architectures, mechanisms for access, privacy and security measures and the appropriate governance to ensure that risks and benefits are balanced.

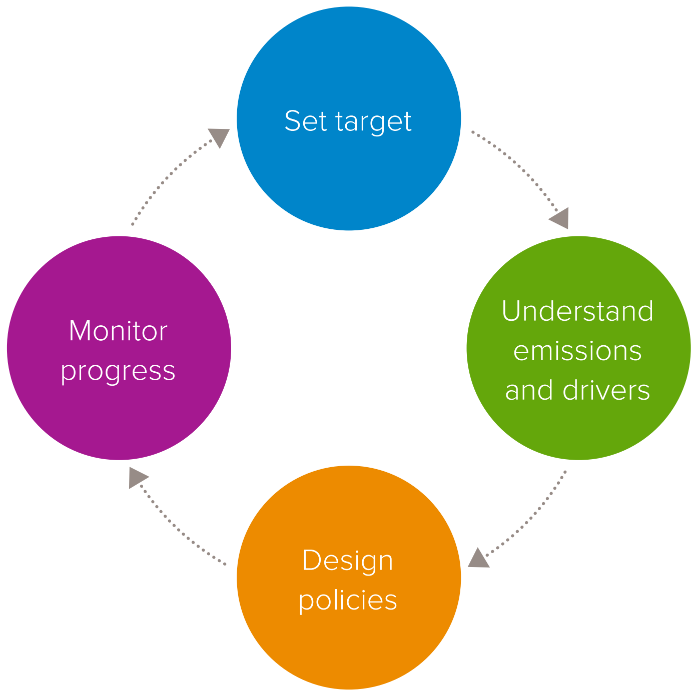
Data for net zero: what data is needed to support the development of digital technologies?

Two types of data are relevant to the development and use of digital technologies for net zero:

- Data on energy use and emissions from land use and from the construction and use phases of buildings, supply chains, transport and other industry assets. Such data will be used to effectively monitor and control emissions, enable carbon accounting, or study trends in climate science or sustainability.
- Data from across sectors about the inner workings of these sectors, from the mapping of physical assets to business processes. Such data will enable the development of digital technologies to reduce, optimise and control emissions.

FIGURE 4

Monitoring progress towards climate commitments.



Current emissions reporting systems support annual accounting, but hardly allow more granular analysis.

Understanding patterns of emissions and energy use

Strategies to tackle climate change rely on setting targets, understanding the current levels of greenhouse gas emissions and drivers of change, designing policies to achieve emissions changes and measuring progress against these (see Figure 4). The UK Government, for example, has committed to the target of 'net zero' greenhouse gas emissions by 2050[77]. To meet this target, it sets a 'carbon budget' for every five-year period. It then accounts for emissions across the economy, reporting progress in reducing emissions on an annual basis.

Assessing progress towards this target relies on carbon accounting and reporting by actors across the economy. Carbon accounting is the process of quantifying physical amounts of greenhouse gas emissions emitted in the atmosphere by a given entity, be it a company or a state. It provides quantitative estimates of emissions and can help assess the impact of different interventions, enabling informed decision-making, for example, about climate mitigation strategies.

There are several ways to report emissions, according to different definitions or with different boundary conditions – depending on frameworks, reporting might or might not include imported emissions, international air travel emissions, or emission removals by land for example[78]. In 2019, the UK updated its requirement for organisations to perform carbon accounting and report emissions, with a new streamlined energy and carbon reporting (SECR) framework[79]. In addition, the Task Force on Climate-related Financial Disclosures recommends that businesses disclose annual Scope 1, Scope 2, and if appropriate, Scope 3 greenhouse gas emissions in yearly company reports[80,81]. Many companies, cities and states follow reporting standards set by the Green House Gas Protocol[82], with the data in standardised format being deposited on the Carbon Disclosure Project's not-for-profit platform, although there is a lag in Scope 3 reporting.

Current emissions reporting systems are based on indicators and proxies, designed to support country-level, city-level, or company-level analysis of emissions on an annual basis. These indicators are less useful in enabling more granular analysis or modelling. For example, existing reporting systems did not support effectively the monitoring of changes in emissions during the first months of the COVID-19 pandemic, and instead scientists have used other proxies and data sources to produce close to real-time estimates (see Box 4)[83]. By identifying exactly which data was necessary, and what constraints were associated with the data, it was possible to generate useful insights.

77. *Op. Cit.* 6

78. Office for National Statistics 2019 Net zero and the different official measures of the UK's greenhouse gas emissions (see https://www.ons.gov.uk/economy/environmentalaccounts/articles/netzeroandthedifferentofficialmeasuresoftheuksgreenhousegasemissions/2019-07-24, accessed 15 October 2020)

79. Carbon Trust 2019 SECR explained: Streamlined Energy & Carbon Reporting framework for UK business (see https://www.carbontrust.com/news-and-events/insights/secr-explained-streamlined-energy-carbon-reporting-framework-for-uk, accessed 15 October 2020)

80. Task Force on Climate-related Financial Disclosures 2019 Status Report (see https://www.fsb-tcfd.org/wp-content/uploads/2019/06/2019-TCFD-Status-Report-FINAL-053119.pdf, accessed 15 October 2020)

81. *Op. Cit.* 63

82. World Business Council for Sustainable Development and World Resources Institute 2004 A Corporate Accounting and Reporting Standard REVISED EDITION. The Greenhouse Gas Protocol. (see https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf, accessed 15 October 2020)

83. *Op. Cit.* 21

BOX 4

The possibilities for enhanced monitoring through data: the example of estimating the impact of COVID-19 lockdowns on carbon emissions.

Estimating the impact of the first weeks of COVID-19 lockdowns on carbon emissions across sectors has required a bottom-up approach to produce daily estimates. Researchers used activity data – as opposed to direct emissions data – for each sector[84]. For example, data from smart meters was used to determine energy consumption from the residential sector.

Accessing such data presented several challenges: most of the data used was not publicly available, this data was less readily available in some sectors than others – while there was good availability of data about emissions of surface transport, it was more challenging to access this from the manufacturing sector – and a lot of that data was proprietary.

The study showed that the UK, like most countries, saw a drop of about 30% in its emissions during the first few weeks of lockdown. The biggest drop came from a reduction in transport, while manufacturing's emissions hardly budged. Over the whole of 2020, depending on the length and strength of lockdowns, the global decrease in emissions was estimated to be around 4 – 7% – similar to the reduction that needs to happen year on year to meet the Paris agreement objectives[85].

Very useful insights in climate science have also come from combining top down approaches to data, using direct atmospheric measurements to infer local emissions, and bottom-up approaches, adding up activity data from each component of the system to infer global emissions. Observable measurements can feed into models, which can then in turn enable the calculation of key control variables using inverse modelling techniques.

A future in which these data types are made more widely available offers new opportunities to monitor global emissions. For example, it may be possible to measure seasonal variations in emissions, or to create new tools for policymakers to monitor the impact of policy interventions intended to reduce emissions.

84. *Op. Cit.* 21

85. United Nations Environment Programme 2019 Emissions gap report 2019 (see https://wedocs.unep.org/bitstream/handle/20.500.11822/30797/EGR2019.pdf, accessed 15 October 2020)

If researchers are to be able to understand emissions contributions from different parts of the earth system, production and transport systems, local-level data will be required. This requires data collection infrastructures that enable the accurate monitoring and tracking of greenhouse gas emissions, such as real-time data from the internet of things (IoT) and satellites, and immutable logs. Data quality may vary, calling for effective data integration tools and agreed data standards.

Such data and digital technologies have the potential to underpin more accurate and dynamic carbon accounting systems. The insights generated by such mechanisms can be used in a range of ways, for example creating new understandings of a complex, global production system and what changes will bring it closer to net zero – is it better to produce solar energy locally, or to produce hydrogen from solar panels in the desert and then transport it to other countries? More accurate and dynamic emissions monitoring would provide crucial feedback in 'control loops' for the planet's emissions. It would also enable evidence-based decision-making on a local level, for example a city. In considering such applications, a first step might be to perform a cost-benefit analysis of the impact of collecting more data compared to better exploiting existing proxy information; the need for more data needs to be balanced with costs such as the administrative burden to business, or the emissions associated with the collection and storage of the new data.

More granular data about the carbon footprint of everyday products and services, presented through intelligible user interfaces, could also help change consumer behaviour. This could build on existing initiatives, which have demonstrated an interest from suppliers to report sustainability metrics to build consumer trust and create shared datasets for benchmarking. An example is the Sustainability Consortium's platform for industry reporting of sustainable information (THESIS). In the US, its uptake has been driven by large distributors joining and requiring their suppliers to report sustainability performance to their commercial procurement departments, illustrating how change towards greater transparency and reporting can be influenced by industry leaders[86].

A protocol or roadmap for data solutions for net zero is needed to clarify how existing data will be made more accessible, and to set out next steps (see Box 5).

Data quality may vary, calling for effective data integration tools and agreed data standards.

86. Over 1500 manufacturers representing almost $1 trillion of consumer products annual sales performed an assessment of their product and supply chain sustainability using The Sustainability Insight System (THESIS). (See https://www.sustainabilityconsortium.org/impact/impact-report/, accessed 15 October 2020)

BOX 5

Towards a roadmap for data solutions for net zero.

A protocol or roadmap for data solutions for net zero would help clarify how existing data will be made more accessible, and to align actors to achieve this goal. This box summarises suggestions received at an expert workshop on the use of data and digital technologies for climate monitoring.

Support more effective use of existing data

Existing datasets can be repurposed, and made more accessible, to enable more effective emissions monitoring. Public institutions such as schools and universities could release data about the emissions they generate – for example, the University of Cambridge built a carbon map with emissions for each building[87] – as a means of demonstrating best practice in data collection and use. There are also opportunities to expand resources that catalogue datasets, such as Resource Watch from the World Resources Institute, which helps researchers identify, utilise and understand the origins of data in an accessible manner[88]. Data from smart meters in particular could be made more accessible for the analysis of trends in household energy consumption.

Characterise the need for further data

There are areas where further data collection would help develop new reporting systems. For example, there is already some data available about transport mobility trends that can be useful in calculating emissions, but such analyses would benefit from more frequent releases. Efforts to create new datasets are not, however, without cost, creating trade-offs in data collection strategies: for example, the need to collect and store data for net zero must be balanced with the need to limit the emissions generated in the process.

Combine multiple sources of data

Combining data from multiple sources can create insights that inform our understanding of emissions from different sources. For example, satellite data can help measure point emissions from sources such as power plants[89,90]. If combined with data from on-the-ground measurements, analysis of such point emissions can be made more accurate.

There might be a role for crowdsourcing the generation of useful data about emissions, but there are substantial issues with the consistency of reporting of individual activity data. For example, in the UK there is a crowdsourcing model for energy consumption where people provide energy meter readings – but this is now being replaced with data emitted directly by smart meters, considered more reliable. There is a role for events such as hackathons in crowdsourcing data mining and helping uncover a breadth of useful data sources. Patterns of data collection also seem likely to change in future, for example it is possible to imagine a world where each building and each vehicle would broadcast its emissions.

87. See https://cambridgecarbonmap.org/ (accessed 15 October 2020)
88. See https://resourcewatch.org/dashboards/climate (accessed 15 October 2020)
89. Nassar R *et al* 2017 Quantifying CO2 Emissions From Individual Power Plants From Space. Geophysical Research Letters, 44, 10,045– 10,053. (see https://doi.org/10.1002/2017GL074702, accessed 15 October 2020)
90. See http://www.copernicus.eu/en/news/news/observer-monitoring-anthropogenic-co2-emissions-copernicus (accessed 15 October 2020)

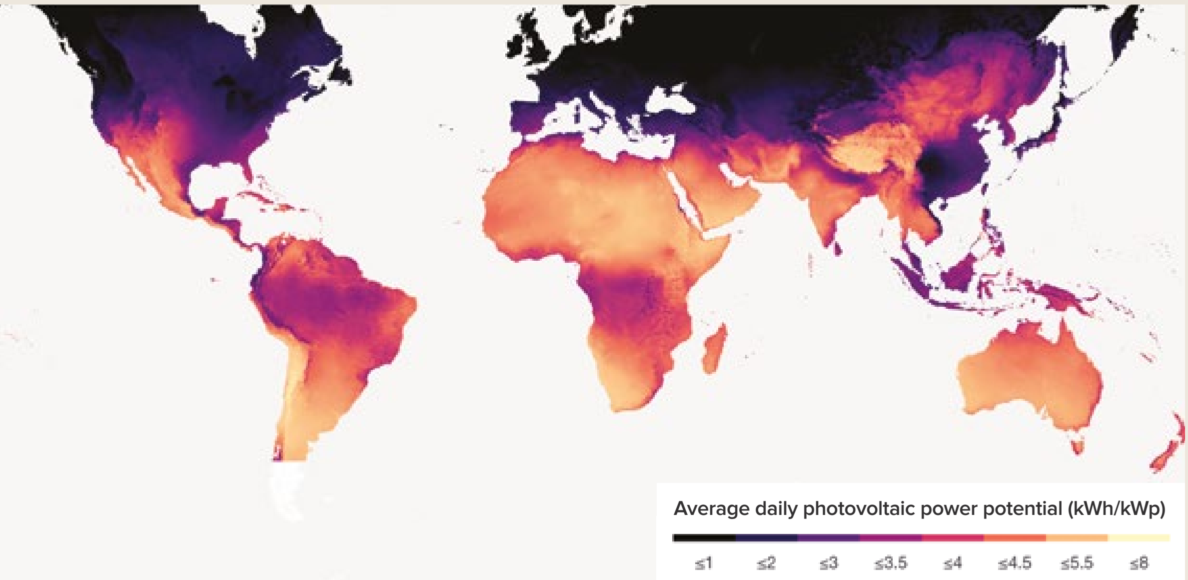


Image
Average Daily Photovoltaic Power Potential (kWh/kWp). Accessed from resourcewatch.org, 18 November 2020.

Build capacity in existing data infrastructures

The UK has already established several high-quality data repositories. The Met Office Informatics Lab, for example, plays a role in calibrating data and in the coordination of agreements around the sharing of weather data, at both a national and an international level. These resources enable accurate weather forecasting across the globe, which is critical for example to improve the response to extreme weather events.

Similar capacities are needed across the world. Currently some regions of the world are much more advanced than others in building data infrastructures, but applications of digital technologies created for use in developed countries do not necessarily work well in in lower income countries. Establishing and maintaining data infrastructures comes at a cost. Depending on cases, it could be more time- and cost-effective to expand the role of existing data infrastructures.

Decision-support apps and software will benefit from integrating a wide range of data.

Data for the development of data-driven technology for net zero

The application examples set out in chapter 1 – data-driven design of more energy-efficient buildings, digital twinning of wind farms to improve their design, operations and maintenance, decision-support tools enabling farmers to make informed crop choices optimising their needs as well as those of the food system – rely on access to data.

If it is made widely available, the data about energy use and emissions discussed above could accelerate the development of digital technologies for net zero. For example, data about the energy performance of individual buildings in their use phase (see Box 6), rather than theoretical, will generate more realistic and useful outcomes from building information modelling. This will be essential to ensure any planned construction works will be most effective in reducing emissions[91,92]. Similarly, significant investment in energy transmission and distribution in Australia, together with associated embodied emissions, could have been minimised if accurate energy demand data was more available[93]. In the UK, the Modernising Energy Data programme and Ofgem are taking forward the Energy Data Taskforce's recommendations towards the digitalisation of the energy sector, which advocated that energy system data be presumed open.

The creation of digital twins for wind farms and other power generation assets will benefit from data about similar assets, their performance and impact. Such data will inform better simulation and therefore better planning of new renewable energy deployments. As digital twins of these new deployments themselves continually generate data, they will feedback information both to the simulated assets and to the wider energy system. In the UK, the National Digital Twin programme envisages an information management framework that will support the connection of digital twins from across sectors, including the natural environment[95] (see Box 6). Several recently announced initiatives are looking to build a planetary scale digital twin, using Earth observation data, in situ measurements and AI to simulate natural and human activity on the planet[96,97].

Many factors come into consideration when deciding what crop to plant in a field: will the crop be resistant and produce high yields given local properties and under upcoming weather conditions? Will the output products be valued on the market or will system-wide overproduction mean a drop in value?

91. Green Alliance 2020 A smarter way to save energy: Using digital technology to increase business energy efficiency (see https://www.green-alliance.org.uk/resources/A_smarter_way_to_save_energy.pdf, accessed 15 October 2020)
92. Green Alliance 2020 Smart building: How digital technology can futureproof UK construction (see https://www.green-alliance.org.uk/resources/Smart_building.pdf, accessed 15 October 2020)
93. Australian Department of Environment and Energy 2019 Case Study: The National Energy Analytics Research (NEAR) Programme in Australia (see https://www.iea.org/articles/case-study-the-national-energy-analytics-research-near-programme-in-australia, accessed 15 October 2020)
94. National Infrastructure Commission 2018 Data for public good (see https://nic.org.uk/app/uploads/Data-for-the-Public-Good-NIC-Report.pdf, accessed 15 October 2020)
95. Hetherington J and West M 2020 The pathway towards an Information Management Framework - A 'Commons' for Digital Built Britain (see https://www.cdbb.cam.ac.uk/what-we-do/national-digital-twin-programme/pathway-towards-information-management-framework, accessed 15 October 2020)
96. See https://www.wcrp-climate.org/wcrp-ip-la (accessed 15 October 2020)
97. European Space Agency 2020 Digital Twin Earth, quantum computing and AI take centre stage at ESA's Φ-week (see https://www.esa.int/Applications/Observing_the_Earth/Digital_Twin_Earth_quantum_computing_and_AI_take_centre_stage_at_ESA_s_Ph-week, accessed 15 October 2020)

Decision-support apps and software will benefit from integrating a wide range of data – data from ground-level sensors and satellites about soil characteristics, precise local weather simulations, and market data including data about the production of regional farms.

Similar examples can be found across sectors, and there are a number of existing initiatives looking to widen access to data with environmental applications (see Box 6). As technological systems that help achieve net zero develop, there will also be further opportunities to make use of even wider sources of data, many of which will not have been collected with this purpose in mind. 'Happenstance data', generated during the operation of a process, is typically not gathered under controlled conditions and this will have consequences for data quality and for the conclusions that can be drawn from the analysis of such data. Such systems may also develop to integrate even more varied sources such as data collected by citizens or reflecting individual behaviours.

How can data for net zero be made more widely accessible?

In addition to the breadth of data to be integrated, the establishment of 'control loops' for the planet will require a flow of data: data from physical assets to train digital models; prediction data from models to optimise physical assets; and continuous feedback. In such control loops, net zero systems will be data-driven and generate data.

In creating a well-governed data infrastructure that enables data access and sharing, four key areas need to be addressed. These can be categorised as follows: technical issues, legal frameworks, ethical and societal dilemmas, and cultural change.

Technical issues

A number of technical issues might limit access to data for net zero. Data might be:

- not easily available in digital formats.
- difficult to find or navigate, or it might not be amenable to digital processing.
- distributed across many organisations, each using different formats, which may change and become out-dated over time.
- of variable quality.
- sensitive and its sharing might require technical safeguards.

To address these issues, several initiatives have developed guiding principles that organisations generating data should apply to ensure a data environment amenable to analysis and machine processing[98]. The FAIR guiding principles for scientific data management and stewardship were developed to improve the Findability, Accessibility, Interoperability and Reusability of data (see Box 7). The FAIR principles help ensure data in a usable, machine-readable form. These principles also help ensure data provenance and quality, which will be discussed in the following chapter on trustworthy technology. Making data available and accessible is also essential to lower the barrier to entry for new companies, which may not have data assets. There are a number of repositories of relevant open data and other initiatives to make data of relevance to net zero more available (see for example Box 6).

Agreeing data standards will also play an important part in ensuring data quality and interoperability, and the UK's Data Standards Authority, with the Office for National Statistics, will have a key role in supporting the global effort in this area. When considering data standards for net zero, the UK Government should seek input from existing standards organisations such as the Climate Disclosure Standards Board and others.

98. *Op. Cit.* 12

BOX 6

Example initiatives to make data with applications for net zero available.

Emissions monitoring capacity – The CO_2 Human Emissions initiative aims to create a system to monitor carbon dioxide emissions across the world. The project consortium is comprised of 22 partners from eight European countries including the UK. A dedicated Data Portal provides an interface to the data used and made available through the project, including observations from satellites, ground-based observation networks and aircraft[99].

Satellite data management and analysis – The Open Data Cube is an international open source project aiming at improving and facilitating the management and analysis of satellite data. It catalogues large amounts of earth observation data and tracks the provenance of data to allow for quality control and updates. Developed on GitHub, the Open Data Cube provides a Python-based API for querying and data access. It builds on the Australian Geoscience Data Cube project[100].

Essential Climate Variables – the Global Climate Observing System lists 54 Essential Climate Variables and lists sources of openly available datasets for each[101].

Weather and climate data – The Met Office, the UK's National Meteorological Service, provides access to weather and climate data and expertise, for businesses and researchers. The Met Office's data services include the provision of Public Sector Information (PSI) data, data available for re-use under license, open data sets available with free access and industry specific data for business use[102].

Environmental data supporting digital innovation – The NERC Digital Solutions programme aims to work with business and public sector users to exploit the rich diversity and potential of public, and possibly commercial, data to create innovative digital services that deliver economic, social and environmental benefits[103].

Data about energy use in buildings – The Chartered Institution of Building Services Engineers (CIBSE) has published an energy benchmarking tool, a platform that will use energy data as it becomes available to provide relevant and reliable benchmarks that represent the current trends of energy use in buildings[104].

Information Management Framework for the National Digital Twin – The Centre for Digital Built Britain's National Digital Twin programme set out a technical approach for the development of an Information Management Framework to enable secure, resilient data sharing across the built environment and across sectors. It seeks to enable an ecosystem of connected digital twins – the National Digital Twin[105].

99. See https://www.che-project.eu/data-portal (accessed 15 October 2020)
100. See https://www.opendatacube.org/ (accessed 15 October 2020)
101. See https://gcos.wmo.int/en/essential-climate-variables/table (accessed 15 October 2020)
102. See https://www.metoffice.gov.uk/services/data (accessed 15 October 2020)
103. See https://nerc.ukri.org/innovation/activities/environmentaldata/digitalsolutions/ (accessed 15 October 2020)
104. See https://www.cibse.org/knowledge/energy-benchmarking-tool-beta-version (accessed 15 October 2020)
105. *Op. Cit.* 95

BOX 7

FAIR data principles.

The FAIR principles[106] emphasise machine-actionability (i.e., the capacity of computational systems to find, access, interoperate, and reuse data with none or minimal human intervention) because humans increasingly rely on computational support to deal with data as a result of the increase in volume, complexity, and creation speed of data.

Findable: Metadata and data should be easy to find for both humans and computers. Machine-readable metadata is essential for automatic discovery of datasets and services.

Accessible: The user needs to know how data can be accessed, possibly including authentication and authorisation.

Interoperable: The data usually needs to be integrated with other data. In addition, the data needs to interoperate with applications or workflows for analysis, storage, and processing.

Reusable: The ultimate goal of FAIR is to optimise the reuse of data. To achieve this, metadata and data should be well-described so that they can be replicated and/or combined in different settings.

GO FAIR's website provides guidance on how to apply the FAIR principles to data in practice. GO FAIR is working together with the Committee on Data (CODATA), Research Data Alliance (RDA), and World Data Systems (WDS) to optimise the global research data ecosystem and to identify the opportunities and needs that will trigger federated infrastructures to service data-driven science.

106. See https://www.go-fair.org/fair-principles/ (accessed 15 October 2020)

Not all data is the same from a legal perspective, and the sharing and use of data for net zero applications needs to account for relevant regulations.

Legal frameworks

Data access needs to be both enabled and controlled by appropriate legal frameworks. For example, data might be protected by intellectual property (IP) rights that limit its access and use. While IP ensures the value of data stays with the individual or organisation that created it, it also imposes conditions on its reuse and potential further value creation. Different kinds of access agreement should be considered to negotiate IP issues, for example distributing the value to be created by sharing data, or creating conditions under which data might be made available. For instance, joint ownership of IP can make it easier for multiple collaborators to decide to provide public access to data they co-generated. The UK's Open Government License encourages the free and flexible use and re-use of information available under this licence, with only a few conditions, offering an example of an approach to follow. In future, new business models might emerge and offer new approaches to handling IP rights – perhaps in a similar way certain digital platforms disrupted the music industry – and thereby facilitate the use of data for net zero.

Legal agreements might also help navigate asymmetries in sectors, in terms of the distribution of the costs and benefits of sharing data. For example, the fragmentation of the energy sector means the costs and benefits of data collection would be spread unevenly across many organisations[107]. Not all data is the same from a legal perspective, and the sharing and use of data for net zero applications will need to account for relevant regulations. For example, raw data from smart meters might contain sensitive personal data. Making such data more widely available will require adequate processes and safeguards to preserve data privacy, in accordance with data protection regulations currently in force in the UK and Europe. Aggregation can be a way to provide data protection, which may be appropriate for a number of uses of data for net zero that can tolerate the loss of information incurred by aggregating data – this needs to be assessed on a case by case basis.

Global cooperative agreements will be needed to facilitate the sharing of data to help achieve net zero. Lessons can be learnt from the sharing of weather data (Box 8) and of data for SDGs (Box 9).

Ethical and societal dilemmas

Ubiquitous data collection, and the subsequent use of data to monitor or influence daily activities for individuals and in organisations, also creates new ethical dilemmas (see chapter 1). The desire to optimise systems to increase sustainability – bringing with it benefits for society – may sit in tension with individual concerns about privacy and surveillance. Ultimately, acceptable uses of data are something to be negotiated socially and politically, and a public conversation about data management and use will also be necessary. There may be a case for new data institutions, such as data trusts, data commons, data collaboratives or data clubs[108,109].

107. *Op. Cit.* 74

108. Data trusts, inspired by legal trusts, enable people or organisations to share data with others, with data governance decisions made by 'trustees' with fiduciary responsibilities (i.e. it is their legal duty to always put their client's best interests ahead of their own). Data commons, inspired by the management of common pool resources, help organisations or people collaborate to create and maintain shared data assets. Data cooperatives, inspired by mutual organisations, enable members of the cooperative (organisations or people) to share data with others, with data governance decisions made by those members. Data clubs, inspired by members clubs, enable organisations to share data with other organisations who are part of the club. Definitions from: https://theodi.org/article/what-do-we-mean-by-data-institutions/ (accessed 15 October 2020)

109. Open Data Institute 2019 Data Trusts summary report (see https://theodi.org/wp-content/uploads/2019/04/ODI-Data-Trusts-A4-Report-web-version.pdf, accessed 15 October 2020)

BOX 8

Data access: the example of weather data.

Numerical weather prediction, the process of obtaining a forecast of a future state of the atmosphere through a mathematical model and weather observation data, is reliant on a range of observations acquired through multinational arrangements, and the UK, through the Met Office, is recognised as providing internationally respected capabilities in this field[110]. The World Meteorological Organisation (WMO), a United Nations specialised agency formed in 1953, forms the backbone of international cooperation in the meteorological community.

Data and derived products are available and exchanged freely and in an unrestricted manner every day between WMO centres and weather offices in each country. There are global cooperative agreements about the sharing of many types of weather data, but not all. For example, rainfall data is critical to improve estimates of the land carbon sink, and while rain gauge data is abundant across the world, it is not currently openly available for research[111]. Only historical weather radar datasets are currently being shared internationally, and not current observations. Some weather data is not shared widely because it has commercial value, but at the same time this commercial value might not be exploited either. Unlocking such data may require a mix of regulatory and cultural changes.

The underpinning technical infrastructure, the WMO Information System is essential to the global exchange of observations data. Interoperability agreements between the WMO Information System and other earth observation networks ensure data, regardless of the source, are leveraged across communities to the greatest extent possible. Continued innovation and cooperation is required to meet the data management challenge of exponentially increasing data volumes and complexity. WMO Information System seeks to harness up-to-date telecommunications capabilities to dramatically increase the amount of data exchanged globally.

Alongside the global meteorological infrastructure that is coordinated by the WMO, the UK Met Office is a member of the Network of European Meteorological Services (EUMETNET). The mission of EUMETNET is to seek to coordinate a consolidated observations network across Europe to ensure that the collective reach of the observations network is greater than the sum of its parts. The UK is also a member of EUMETSAT, which operates both geostationary and low Earth orbiting satellites carrying a variety of sensors essential for observing weather and climate. EUMETSAT exists in order to leverage the collective resources of all the member states, none of whom would be able to operate such a satellite programme in isolation. The data provided by satellites is essential for effective numerical weather prediction and is the single highest contributing data type to the accuracy of the forecast.

110. The Royal Society 2015 Observing the Earth: Expert views on environmental observation for the UK (see https://royalsociety.org/-/media/policy/projects/environmental-observation/environmental-observations-report.pdf, accessed 15 October 2020)

111. UNFCCC Subsidiary Body for Scientific and Technological Advice (SBSTA) (2018) Summary report on the tenth meeting of the research dialogue (see https://unfccc.int/documents/183867, accessed 15 October 2020)

A number of organisations and initiatives have established principles to guide the ethical use of data and data-driven technologies[115,116]. The Royal Society and British Academy's *Data management and use: governance in the 21st century* report considered a set of principles that should guide data management and use[117]. Its core message – that data use should support 'human flourishing' – signifies that organisations that hold data should make decisions about data management, sharing and use, with benefit to humanity as a guiding consideration.

BOX 9

Data access: the example of data for Sustainable Development Goals.

The United Nations report *A World That Counts*[112] emphasised the criticality of mobilising the data revolution for sustainable development, both to monitor and achieve the Sustainable Development Goals. A group of governments, companies, and civil society organisations came together to launch the Global Partnership for Sustainable Development Data, working to create a world where good data is used to achieve just and sustainable societies. The Global Partnership does this by:

- Strengthening inclusive data ecosystems by working with governments to develop National Partnerships for Sustainable Development Data, driving data collaborations to achieve national priorities for change.
- Forging collective action by driving global collaboration to improve the production and use of data in critical areas.
- Communicating the value of investing in data and of multi-stakeholder collaborations on data.
- Mobilizing stakeholders to develop global data principles and protocols for sharing and leveraging privately held data.
- Bringing together multiple data communities at global and national level to spur innovation and collaboration.
- Harmonizing data specifications and architectures, and helping ensure the interoperability of technology platforms for assembling, accessing, and using data.

It draws on contributions in data, skills, knowledge and resources from the partners. The Office for National Statistics (ONS) is coordinating and reporting on the global SDG indicators for the UK. The ONS also contributed to Open SDG, an open source, free-to-reuse platform for managing and publishing data and statistics related to the UN Sustainable Development Goals (SDGs)[113]. It is built exclusively with open-source libraries and tools and can be hosted and maintained using free services. Its key features include machine-readable data and data visualisations such as graphs, data tables and maps. The UN Environment Programme is also working towards a Global Environmental Data Strategy, including the establishment of a knowledge platform making environmental data permanently available to Member States[114].

112. Gonzales Morales L *et al* 2014 A world that counts: Mobilising the data revolution for sustainable development (see https://www.undatarevolution.org/report/, accessed 15 October 2020)

113. See https://open-sdg.readthedocs.io/en/latest/ (accessed 15 October 2020)

114. United Nations Environment Programme 2019 Background Document for Agenda Item 4: Implementation of UNEP/EA.4/HLS. 1 Ministerial Declaration (see https://wedocs.unep.org/bitstream/handle/20.500.11822/29753/Item%204%20UNEP_UNEA4_Monitoring_Ministerial_Declaration-Thu-12-Sep-2019.pdf, accessed 15 October 2020)

Technological approaches can help manage some of the ethical concerns associated with data use. For example, Privacy Enhancing Technologies (PETs) can enable data sharing and data analysis whilst protecting sensitive information, provided they are supported with the right processes and governance frameworks[118]. For instance, some of these technologies can enable decentralised approaches to data analysis, so that data stays on an individual device and processing is performed locally. Other PETs could allow multiple organisations to run an analysis on their combined data without revealing their respective datasets, which might contain data about individuals or business-sensitive data. This might be helpful for farmers to take part in an analysis on regional food production without revealing their individual input to competitors; this would enable farmers to make informed decisions on crop choice, harvest time, and pricing, in ways that help secure farmers' revenues as well as regulate systemic production and reduce waste. Frameworks for the safe sharing and use of data for net zero might combine technical – such as through the use of PETs – and legal arrangements.

Cultural change

The culture in organisations or sectors might limit the collection, use and sharing of data. Many companies hold on to data without exploiting it, and a cultural change is needed towards greater openness for the good of the planet.

Conversely, in many sectors, data collection and use are currently treated as an 'extra' rather than a core business process; achieving data-enabled transformations will require businesses to understand the strategic value of data[119,120], and how to create value from generating and sharing data resources. Generating shared insights is one of the reasons business decide to share data with third parties[121]. Fiscal measures such as tax credits could also be employed to incentivise greater data sharing.

A number of organisations or sectors might be wary of the risks posed by increased data collection and use[122]. Beyond data about individual and privacy risks, organisations might be reluctant to share information deemed too sensitive and may need to find ways to manage the corresponding dilemmas in data use. For example, sharing data about critical infrastructure, such as energy systems, without adequate protection may pose a cybersecurity risk and a threat to system resilience.

By developing specific exemplar projects and sharing learnings, the UK Government's new Integrated Data Platform led by ONS has an opportunity to lead the way and increase confidence in linking and using data for net zero.

The major public health crisis caused by COVID-19 has disrupted to some extent cultural barriers to data collection, sharing and use. Achieving net zero by 2050 is another major societal challenge, albeit of a different nature, but which could also prompt a cultural change enabling the greater use of data for the planet.

Generating shared insights is one of the reasons business decide to share data with third parties.

115. *Op. Cit.* 14
116. See https://www.ons.gov.uk/aboutus/transparencyandgovernance/datastrategy/dataprinciples (accessed 15 October 2020)
117. *Op. Cit.* 14
118. *Op. Cit.* 15
119. Open Data Institute and Bennett Institute for Public Policy 2020 The value of data (see https://theodi.org/article/the-value-of-data/, accessed 15 October 2020)
120. Open Data Institute 2020 R&D: The value of data sharing in the private sector (see https://theodi.org/project/the-value-of-data-sharing-in-the-private-sector/#1586851401550-1bd51203-8c59, accessed 15 October 2020)
121. Open Data Institute 2020 Case study: The value of sharing data to address sector challenges (see https://theodi.org/article/case-study-the-value-of-sharing-data-to-address-sector-challenges/, accessed 15 October 2020)
122. *Op. Cit.* 74

Recommendations

Data will be at the core of the net zero transition, enabling emissions monitoring as well as data-driven applications and services underpinning emission savings across sectors.

RECOMMENDATION 1

The net zero transition should be data-led, with governance arrangements in place that enable the safe and rapid use of data to support the achievement of the net zero target:

- As part of the COP26 effort and future international engagement, the UK Government should lead on the creation of international arrangements to enable the collection, sharing and use of data to underpin the development of applications and services helping achieve net zero. A key aspiration should be the establishment of a flow of data making planetary digital twins and a control loop for the planet possible. For the latter, data about a number of essential climate variables need to be made more widely available, for example measured atmospheric composition and concentration, and rainfall data, which is important for estimating the future land carbon sinks and should be shared widely on a global level.
- To ensure the transition towards a low-carbon economy harnesses the potential of data and digital technology, there needs to be coordination between initiatives happening across government, regulators, industry and the third sector. To this end, the UK Government should be informed by a cross-departmental and cross-sector taskforce devoted to the digitalisation of the net zero transition[123] and ensuring these initiatives are connected and amplified. It should identify immediate policy interventions and develop a roadmap for the digitalisation of the net zero transition, setting out priority use cases for existing data, actions to increase data access and use, and priorities regarding new data collection and analyses. It should ensure that data that can help achieve net zero follow the FAIR principles (Findable, Accessible, Interoperable, Reusable).
- Data for emissions monitoring: In order to accelerate the systematic collection of robust data about businesses' energy use and emissions across sectors, the taskforce for the digitalisation of the net zero transition should work with the science community and business to review standards for reporting Scope 1, Scope 2, and Scope 3 greenhouse gas emissions – respectively associated with energy use, the energy mix involved, and upstream and downstream emissions. This should consider the temporal and spatial sampling of published data that would support greater monitoring of supply chain emissions and intervention impacts.

123. The digitalisation of the net zero transition means a transition that involves collecting quality data on emissions and energy use and that uses that data to create innovative solutions and bring down energy use and emissions. A transition that makes the greatest use of digital technology and digital services to reduce energy use and emissions, in ways that serve all of society. Also see Box 1.

- Data that can help achieve net zero should be made accessible through appropriate arrangements. Wherever possible it should be made open, while adequately addressing social and ethical dilemmas in data use. Where data cannot be made fully open, appropriate and robust frameworks should be in place, such as data access agreements or data trusts. In the case of datasets containing sensitive data, data might be made more shareable through privacy-preserving approaches including anonymisation, synthetic data generation and other approaches. For example, smart meter data should be made open after applying differential privacy or equivalent approaches to prevent the identification of any single household.

RECOMMENDATION 2

The UK Government has a responsibility to set an example of best practice through well governed use of data.

When implementing the National Data Strategy, Government should ensure data strategies and data standards across government departments and regulators function to facilitate data use and promote trustworthy technology use. This should build on the Centre for Data Ethics and Innovation's work on public sector data sharing, to overcome barriers to data sharing and address citizen trust. Through low-carbon, outcome-focused procurement and through sponsoring pathfinder studies, Government can lead the way in driving development and adoption of digital technologies for net zero, modelling their use for others and engaging regulatory bodies in identifying the data sharing agreements and other frameworks needed to support such applications.

Chapter three
Trustworthy technology

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Trustworthy technology

Three design factors are essential in developing technologies to help tackle climate change – contestation, participation and resilience.

By integrating data from across different sources or organisations, and identifying points of intervention to reduce a system's emissions, digital technologies can enable more effective human management of complex systems – whether transport, land use, or energy networks. To fulfil this potential, these technologies will need to be designed in ways that work well for people. Recent years have already seen much policy interest in the design of trustworthy technologies, and the interventions needed to give people confidence in the use of digital technologies. In developing this work, the implementation of digital systems to achieve net zero will need to take into account three further design factors that are particularly important in developing technologies to help tackle climate change – contestation, participation and resilience.

Contestation: embedding the ability to challenge the outputs of emissions control loops

Contestation refers to the idea that individuals should be able to challenge and verify the outputs from a digital system, acknowledging the fact that any systems will have limitations. It implies mechanisms that enable users or those affected by the output of a system to interrogate the information digital systems produce, to understand why a system has produced a specific result, and to hold decision-makers accountable for the use of digital technologies and the decisions based on their insights. Technology-based approaches can improve the ability to contest an outcome, introduced below – data provenance, explainability and auditability – but wider systems of accountability and governance frameworks might be needed, including standards and regulations[124].

Data provenance: ways to log and check how data is being used

Many of the digital technology applications that can help reduce emissions rely on the ability to integrate data from multiple sources, analysing this to optimise a system or predict future demands on it. For example, those who operate office buildings might use data-enabled support tools to make decisions about patterns of lighting and heating. This might rely on data about how many people are logging into work, from what room, weather conditions, local renewable energy generation and other sources of information. Decision-support tools will need to integrate multiple sources of data, and the relevance of the conclusion will depend on the quality of the input data.

Data infrastructures to enable net zero will need to be supported by systems that manage data provenance in a reliable manner. One way to interrogate control loops for the planet will be to inspect data logs, to follow the journey of data, from the original raw data to the final actionable information. Data provenance refers to a form of metadata that records the history and context of the data, from its creation to its latest modification. This information can help assess data quality and its relevance to a particular analysis. The FAIR data principles (that this report advocates) highlight the importance of metadata in making data usable. 'Datasheets for datasets' is another approach to data logs, advocating that each dataset should be documented with a datasheet[125].

124. For example, standards might specify the boundaries for trustworthy emission reporting.

125. Gebru T *et al* 2018 Datasheets for Datasets. arXiv:1803.09010 (see https://arxiv.org/abs/1803.09010, accessed 15 October 2020)

Blockchain-style technologies offer another approach to data provenance, with an additional guarantee of the immutability of data records. Such methods can be energy-intensive and should not be employed indiscriminately[126]. The distributed immutable records provided by blockchain might be justified in areas that require greater accountability, and these technologies are being piloted for example in the food and fashion sectors[127,128]. In the context of digital technologies for the planet, such properties could be important for applications to emissions monitoring and reporting. Such technologies could enable the accurate tracing of emissions across supply chains.

Explainability: enabling individuals to interrogate the output of digital systems for net zero

Achieving the potential of digital technologies as decision-support tools requires digital systems that work well for people, and which they can interrogate and challenge, allowing human users to bring additional contextual understanding or judgment to bear on the operation of the system. In some applications, users may need to understand how a digital system has reached a decision, or require information to be provided in ways that are useful in supporting decision-making. For example, energy systems operators will need to be able to interrogate, and examine through the lens of their domain knowledge, how an AI system made a recommendation about switching on or off part of the energy grid and distributed storage capacity. Although less critical, AI-enabled dashboards making recommendations to individuals about lifestyle choices will give people greater confidence if they provide details about how they process data about individual habits, options on the market, financial costs and emissions.

Some of today's digital tools are able to produce highly-accurate results, but are also highly complex. So-called 'black box' models can be too complicated for even expert users to fully understand. As complex digital systems become embedded in decision-making processes, there are increasing concerns about this lack of 'explainability'.

There are different technical approaches to achieving explainability[129]. For example, one way to provide transparency is to publish the algorithm or simulation being used to analyse data, and to give clarity about the framework within which it operates. While enabling some form of public scrutiny, this approach is not well-suited to enabling non-expert communities to engage with or challenge why a particular output has been reached. Another approach is to use inherently interpretable models, whose structure and function is easily understandable by a human user. This too has limitations, restricting those developing algorithmic systems to use of relatively simple models. Where such complex models are required, some degree of explainability can be achieved through the use of proxy models, which approximately match the system of interest and are interpretable, or through the development of mapping tools that help visualise which input features led to a particular output.

126. Monrat, A.A., Schelén, O., and Andersson, K., 2019. A survey of blockchain from the perspectives of applications, challenges, and opportunities. IEEE Access, 7: p. 117134-117151. (see http://ltu.diva-portal.org/smash/get/diva2:1343319/FULLTEXT01.pdf, accessed 15 October 2020)

127. Food Standards Agency 2018 FSA trials first use of blockchain (see https://www.food.gov.uk/news-alerts/news/fsa-trials-first-use-of-blockchain#:~:text=The%20Food%20Standards%20Agency%20has, accessed 15 October 2020)

128. The LuxTag Project 2019 How Is Blockchain Technology Changing the Fashion Industry? (see https://medium.com/luxtag-live-tokenized-assets-on-blockchain/how-is-blockchain-technology-changing-the-fashion-industry-3211d745d064, accessed 15 October 2020)

129. The Royal Society 2019 Explainable AI: the basics (see https://royalsociety.org/-/media/policy/projects/explainable-ai/AI-and-interpretability-policy-briefing.pdf, accessed 15 October 2020)

Continued auditability and transferability of data, eg about a vehicle's emissions, would bring greater accountability.

Different users require different forms of explanation in different contexts[130]. For example, system developers might require technical details about how algorithms function, regulators might require assurance about how data is processed, and householders might want their smart meters to provide accessible, synthetic information through an intuitive user interface. The approach to explainability should be chosen carefully: the more critical a digital system for net zero, the more accurate and faithful an explanation is required. The risk of an explanation not being accurate enough is low in the case of an app helping a user choose the least polluting route, it is much greater when it comes to digital interfaces informing grid operators.

Those developing and deploying digital decision-support tools in the context of net zero will need to consider these different needs, for example through participatory design[131] approaches. They will also need to consider whether the explanations such digital systems provide are reliable, whether there is a risk that explanations might deceive their users, or whether they might contribute to gaming of the system or opportunities to exploit its vulnerabilities.

Auditability: enabling accountability in the digital infrastructure

Auditability refers to the ability to establish whether a system is functioning adequately – this can be important in helping developers understand whether a software is operating as expected, and can play a key role in the enforcement of standards and regulations.

For example, if a digital twin of a factory generates information about emissions from its physical counterpart, and this forms the basis of official sustainability reporting, this digital twin needs to be auditable so that the validity of its output can be verified. Auditability will be particularly important to enable regulators to verify greenhouse gas emissions data and, on this basis, to hold organisations accountable. One-off testing approaches might not be robust enough and might not be sufficient to support accountability. For example, vehicle emissions testing was rigged by software that detected and responded differently to test conditions[132].

An alternative approach to auditability, bringing greater accountability, would be based on continued auditability and transferability of data. For example, connected cars could transmit a readout of their emissions through Bluetooth, which could then be monitored by other devices. This would provide reliable information about vehicle emissions in use.

Auditability will also be essential to ensure data-driven systems developed to help achieve net zero do not embed systemic biases. For example, during the transition to net zero there might be correlations between less well-off neighbourhoods and low building energy performance, if renovations happen faster elsewhere – auditability should help ensure such correlations do not result in bias against those demographics. The Information Commissioner's Office provides guidance on auditing AI systems and mitigation of potential discrimination[133].

130. *Op. Cit.* 129

131. Participatory design refers to an approach to design attempting to actively involve all stakeholders in the design process to help ensure the result meets their needs and is usable.

132. BBC (2015) Volkswagen: The scandal explained (see https://www.bbc.co.uk/news/business-34324772, accessed 16 October 2020)

133. Information Commissioner's Office 2020 Guidance on AI and data protection (see https://ico.org.uk/for-organisations/guide-to-data-protection/key-data-protection-themes/guidance-on-artificial-intelligence-and-data-protection/, accessed 16 October 2020)

While greater monitoring and transparency would enhance auditability, it may also raise privacy concerns. Those who develop and deploy digital systems in the context of net zero will need to manage the dilemma between transparency and privacy carefully. Privacy Enhancing Technologies (PETs) offer an opportunity to disclose information whilst protecting sensitive data[134]. For example, there might be a role for federated learning or secure-multi-party computation in enabling smallholder farmers to contribute to models and analyses about supply and demand across the food system, without sharing sensitive business information they fear might unfairly benefit others in the food supply chain.

Participation: designing and deploying digital systems for net zero that work for everyone

Participation is also central to the success of digital technologies deployed in the context of net zero. It has many dimensions, including technology design, policy design and participation in the auditing process. In considering data use, different companies, communities and individuals will have different priorities and concerns, and data access solutions and applications that are acceptable to one group might not be acceptable to another. A collective understanding of purpose, effective stakeholder dialogue and participatory design[135] ensuring inclusion and representation in decisions about technology use, as well as open approaches to technology development, will all be important.

Communicating purpose and shared benefits

Creating widespread buy-in and support for the collection and use of data for net zero will require a collective understanding of the shared challenge posed by climate change, as well as clarity about the purpose of data collection and computing for the planet. For example, initially householders were told that smart meters would help gain insight into their energy use and help them save money[136], while another goal from smart meters is to reduce emissions. If smart meters deliver on the latter while only marginally saving money this could have implications for trust.

'Who benefits?' is a key question raised by members of the public when evaluating the use of data and digital technologies[137]. In seeking to achieve net zero, there is a challenge linked to the disconnect between personal and communal benefits from sharing data in order to reduce emissions. Communal benefits are generally less immediately tangible to people, and therefore valued less in comparison to personal benefits[138]. There is an opportunity here to learn from the sharing of patient data, as research shows that people are willing to share data to progress research and benefit the community, even if it does not directly benefit them[139]. It will be particularly important to communicate progress with the use of data to achieve the net zero target over time, making communal benefits visible. All types of benefits – to individuals and to the community – may be motivators and should be conveyed to the public.

134. *Op. Cit.* 15

135. See footnote 131

136. Grantham Research Institute on Climate Change and the Environment and London School of Economics and Political Science 2019 Why the UK's smart meter rollout needs to be smarter (see https://www.lse.ac.uk/granthaminstitute/news/why-the-uks-smart-meter-rollout-needs-to-be-smarter/, accessed 16 October 2020)

137. The Royal Society and Ipsos MORI 2017 Public views of Machine Learning: Findings from public research and engagement conducted on behalf of the Royal Society (see https://royalsociety.org/~/media/policy/projects/machine-learning/publications/public-views-of-machine-learning-ipsos-mori.pdf, accessed 16 October 2020)

138. The Royal Society 2017 Data governance: public engagement review (see https://royalsociety.org/-/media/policy/projects/data-governance/data-governance-public-engagement-review.pdf, accessed 16 October 2020)

139. See https://understandingpatientdata.org.uk/how-do-people-feel-about-use-data (accessed 16 October 2020)

Real world experiments, or 'living labs', helped understand the needs of vulnerable households when using smart appliances.

Continuing with the example of smart meters, saving money might be as compelling an incentive to householders as contributing to more accurate modelling of energy demand through sharing smart meter data.

Effective stakeholder dialogue

To be effective, the governance of data and its use needs to be grounded in effective stakeholder engagement, drawing insights from publics, policymakers, regulators and researchers[140]. Such engagement needs to include activities which consider the context-specific nature of data use, seek thoroughly considered and representative viewpoints, and engage deeply with the complex social and technical issues that sit at the heart of these challenges. In the context of digital applications for net zero, stakeholder dialogues might explore the dilemmas outlined in chapter 1: for example, the need to collect data about patterns of behaviours will need to be balanced with concerns of surveillance. For instance, engagement with a range of stakeholders about the collection and use of data in the energy sector highlighted underuse of collected data as a substantial risk that could undermine trust[141].

Substantive public engagement can contribute to better decision-making and create more socially robust scientific and technological solutions[142,143]. Technological developments and dialogue will need to happen in parallel, in a way that ensures risks and benefits are shared across society. As digital technologies accelerate the transformation of sectors towards net zero, in-depth research and dialogue will be necessary to ensure the transformation works for everyone. Research by Citizens Advice and by the Energy Systems Catapult produced insight that will be useful in shaping energy services and markets, and outlined opportunities for energy suppliers to improve in providing customer service[144,145]. For example, research on how people understand the benefits of smart appliances concluded that, in the short term, it is crucial that companies test and trial different ways to give people information about energy smart appliances and offers; and that investing in good customer advice and support will be essential for dealing with queries and problems as this market develops[146]. Real world experiments, or 'living labs', helped understand the needs of vulnerable households[147]. The Energy Systems Catapult compiled a manual to help energy innovators, policy makers, SMEs, and local authorities deliver smart energy innovation that ensures consumer protection[148].

140. *Op. Cit.* 14

141. Centre for Data Ethics and Innovation 2020 AI Barometer report (see https://www.gov.uk/government/publications/cdei-ai-barometer, accessed 16 October 2020)

142. Wilsdon J and Willis R. 2004 See-through Science: Why public engagement needs to move upstream. (see https://www.demos.co.uk/files/Seethroughsciencefinal.pdf, accessed 16 October 2020)

143. See www.climateassembly.uk (accessed 16 October 2020)

144. See https://www.citizensadvice.org.uk/about-us/policy/policy-research-topics/energy-policy-research-and-consultation-responses/energy-policy-research/ (accessed 16 October 2020)

145. Energy Systems Catapult 2020 Fuel poverty in a smart energy world: How vulnerable consumers could benefit from smart heating controls (see https://es.catapult.org.uk/reports/fuel-poverty-in-a-smart-energy-world/, accessed 16 October 2020)

146. See https://www.citizensadvice.org.uk/about-us/policy/policy-research-topics/energy-policy-research-and-consultation-responses/energy-policy-research/powering-up-or-facing-resistance-how-people-understand-the-benefits-of-smart-appliances1/ (accessed 16 October 2020)

147. *Op. Cit.* 145

148. Energy Systems Catapult 2020 Smart Consumer Protection Manual (see https://es.catapult.org.uk/brochures/smart-consumer-protection-manual/, accessed 16 October 2020)

Attitudes to the collection and use of data with applications for net zero may vary over time and multiple points of engagement are necessary[149]. Rather than relying on individual dialogue projects as a means of creating spaces for members of the public to exert some form of agency in decision-making, alternative approaches are necessary. An infrastructure that creates spaces for public debate offers a different form of agency. Bottom-up infrastructures, such as data trusts, could be well-placed to offer such platforms for engagement, taking into account evolving technologies, data uses, or perceptions of benefit. Social media monitoring or online forums would also potentially be useful tools to better map the contours of public debate, and to understand how these change over time and across society[150].

Concerns about negative consequences of data use might vary for different parts of the population, and different risks may arise that affect specific ethnic or socioeconomic groups. For example, greater monitoring of patterns of behaviours – such as systematically analysing purchase histories to establish personal carbon footprints – could lead to stigmatisation of, or discrimination against, certain groups. Participatory design, drawing on approaches such as Delphi surveys, dialogues and citizen juries, will be essential to surface such risks and identify ways of managing them to maintain public confidence. There is further work to ensure that a range of voices are well-represented in conversations about data policy and in the co-design of digital solutions for net zero[151]. Tackling this concern requires actions to engage effectively across a wide range of civil society stakeholders, while also seeking to diversify the community of people working on data governance issues and digital technology development underpinning applications for net zero.

Open approaches to technology development and use

New business models can provide open approaches to technology development and use, enabling both participation of a more diverse community of developers and greater scrutiny of these systems. The computer science community typically strives for a culture of making code open and available for all to inspect, improve and build on ('open source software'). This presents an opportunity to promote greater transparency, participation and trust in the digital infrastructure for net zero.

An example of this is LowRISC, a community interest company implementing open source designs with a root of trust mechanism which is publicly inspectable[152]. Google have adopted LowRISC's root of trust mechanism[153]. A hardware root of trust is a physical source that can always be trusted within a cryptographic system, for example Google uses root of trust chips to ensure that its data centres boot from a known trustworthy state with verified code. Google, LowRISC and their partners want to spread the benefits of such root of trust chips, through 'open source silicon' – similarly to open source software. Building on this example, third-party organisations, or an ecosystem of such entities, could be conceived that would provide technical means so that the public can

Open approaches to technology development can promote greater transparency, participation and trust in the digital infrastructure for net zero.

149. The Royal Society and Centre for Data Ethics and Innovation 2020 Engagement as a mode of operation: public dialogue and policymaking in data and digital technologies (see https://royalsociety.org/-/media/policy/projects/ai-and-society/RS-CDEI-Roundtable---Note-of-Discussions.pdf, accessed 16 October 2020)

150. *Op. Cit.* 149

151. Young M *et al* 2019 Toward inclusive tech policy design: a method for underrepresented voices to strengthen tech policy documents (see https://link.springer.com/article/10.1007/s10676-019-09497-z, accessed 16 October 2020)

152. See https://www.lowrisc.org/about/ (accessed 16 October 2020)

153. Protalinski E 2019 Google announces OpenTitan, an open source silicon root of trust project (see https://venturebeat.com/2019/11/05/google-announces-opentitan-an-open-source-silicon-root-of-trust-project/, accessed 16 October 2020)

Currently, people can make a data connection on demand to a 4G network 98.7% of times, a reliability level below that of electricity supply in the UK (99.992%).

inspect digital systems for net zero. It would license its products at low cost. This could support a model of operating in which large tech companies would provide digital services for net zero, and community interest companies would provide a root of trust mechanism.

Whether such trusted third-party organisation(s) should operate at an international level, national or local level is open for debate. On the one hand, organisations at a local level might be better able to respond to local challenges, for example in setting up district heating. On the other, organisations operating at such a local level might be faced with a capacity issue, with implications for data management and the ability to use it to help achieve net zero. Crucially, people report differing levels of trust in different types of organisations[154]. This dilemma could be explored in future stakeholder engagement activities.

Resilience: ensuring a secure, adaptable digital infrastructure for net zero

Resilience – the ability to function, adapt, grow, learn and transform under stress or in the face of shocks – will help organisations deliver systems that are reliable and secure. Resilient organisations can better protect their customers, provide more useful products and services, and earn people's trust – this requires secure and trustworthy digital systems[155]. As critical infrastructure for the planet, computing must be resilient to a range of shocks and stresses, and be able to adapt and transform to longer term risks and opportunities. The critical digital infrastructure for net zero will need to demonstrate, in particular, reliable service availability, an ability to operate on different scales, cybersecurity, longevity and interoperability, and flexibility as well as robustness.

Service availability

Smart energy grids and other critical digital systems for net zero will need to ensure continued service provision. The National Infrastructure Commission proposed a framework for resilience for critical infrastructure, including digital, which will need to be observed in the development of resilient critical digital infrastructures such as smart grids[156]. The Commission recommended in particular that, with the help of regulators, Government set resilience standards and that infrastructure operators should carry out stress tests to ensure their systems meet those standards. The Commission notes the following as a good example of standard for digital service availability: Ofcom's general conditions require communications providers to maintain uninterrupted access to emergency organisations "to the greatest extent possible", with significant fines for failures.

If energy grids are to be digitised, the underlying data networks will need to demonstrate a new level of reliability. Currently, people can make a data connection on demand to a 4G network 98.7% of times[157], a reliability level which trails behind that of electricity supply in the UK (99.992%)[158].

There are also risk multipliers if interconnected systems are all reliant on one underlying piece of communications infrastructure. If smart homes with heat pumps and electric vehicle chargers all rely on the internet to operate, households could potentially be without heating or mobility if there are internet issues.

154. *Op. Cit.* 149

155. *Op. Cit.* 11

156. National Infrastructure Commission 2020 Anticipate, React, Recover: Resilient infrastructure systems (see https://nic.org.uk/app/uploads//Anticipate-React-Recover-28-May-2020.pdf, accessed 16 October 2020)

157. Ofcom 2019 The consumer mobile experience (see https://www.ofcom.org.uk/research-and-data/telecoms-research/mobile-smartphones/consumer-mobile-experience, accessed 16 October 2020)

158. Ofgem 2019 Network performance summary 2018-19 (see https://www.ofgem.gov.uk/system/files/docs/2020/02/riio-ed1_network_performance_summary_2018-19.pdf, accessed 16 October 2020)

The ability to operate on different scales

With COVID-19 lockdowns meaning videoconferencing and online meetings have become more common, there has been a recent expansion in the demands on our digital systems. That these digital infrastructures have functioned so effectively indicates that new digital-enabled ways of working are possible and could be widespread. To achieve this, these digital applications will need to scale.

Creating a control loop of the planet will demand a higher level of connectivity in the system, and digital systems and infrastructures developed today should be designed with this next level of connectivity in mind. Developers and engineers will need to design systems and digital technologies so that they can operate on a range of scales. The existence of multiple sub-systems, that could run independently if needed, might also make the system more resilient. For example, a variety of scales, locations and types of renewable generation provides resilience to a national grid, in case of a heat wave or flooding that would affect only one part of the country. Similarly, an energy system control loop might be more resilient if it were built of multiple, smaller control loops regulating different parts of the system. The balance between edge and centralised control will be crucial in ensuring that a loss of communication connectivity does not lead to an outage and that the electricity system can continue to operate safely ('fail stable').

Cybersecurity

Digital systems for net zero, for example smart grids, might be subject to cyberattacks. As critical infrastructure, they will need a high level of protection. State-of-the-art cybersecurity technology will be needed to support trustworthy digital systems[159]. Energy grid operators, and those who operate the digital twins of critical assets in other sectors, ought to implement the highest standards of cybersecurity, following guidance from the National Cyber Security Centre. An increasing number of connected devices, for example smart meters, heat pumps and electric vehicles in distributed electricity grids, also means more points of entry for malware and cyberattacks. Control loops for the planet will require continued policy efforts to ensure a safe and secure Internet of Things (IoT)[160].

Longevity and interoperability

Resilience of digital systems over time is also affected by whether digital technologies are built to last and by their interoperability – whether they are built to function easily in conjunction with other parts of the system. Interoperability is key to machine-to-machine communication and, therefore, to achieving the full potential of digital technology. Users might reasonably expect both longevity and interoperability from digital technologies, and the failure to fulfil these criteria can damage the trustworthiness of these technologies and the organisations providing them.

For example, the smart meter roll out in the UK has been complicated by the fact that the first generation of meters lacked interoperability[161]. This has meant that householders who were promised greater functionality from having a smart meter may now be unable to have this, if they have switched to another energy provider without a device upgrade. The second generation of smart meters now has better interoperability. All IoT devices deployed in digital systems for net zero, including those deployed in smart homes, should adopt the higher standards of interoperability and longevity seen in Industrial IoT.

IoT devices deployed for net zero, eg in smart homes, should adopt the higher standards of interoperability and longevity seen in Industrial IoT.

159. *Op. Cit.* 11

160. The Royal Academy of Engineering 2018 Internet of Things realising the potential of a trusted smart world (see https://www.raeng.org.uk/publications/reports/internet-of-things-realising-the-potential-of-a-tr, accessed 16 October 2020)

161. Hinson S 2019 Energy Smart Meters. House of Commons Library. Number 8119, 7 October 2019. (see http://researchbriefings.files.parliament.uk/documents/CBP-8119/CBP-8119.pdf, accessed 16 October 2020)

Unexpected events could disrupt the digital infrastructure for net zero, and redundancy in the system is a way to increase adaptability and resilience.

The longevity of devices also has implications for the overall sustainability of the technology sector, with increased longevity reducing the frequency with which sensors need to be replaced, and in turn reducing the emissions associated with the manufacture of new devices and disposal of old ones. Both longevity and interoperability bear obvious implications for the carbon footprint of digital technologies and should be an integral part of future roll-outs of IoT devices and other digital infrastructure.

Building in flexibility

Flexibility, the ability to adapt to new circumstances, is an important aspect of resilience. The digital infrastructure for net zero should be built in a way that can allow multiple possible future developments, and respond to a range of new circumstances.

There is a tendency to equate digital transformation with optimisation for efficiency. Computing models should not be optimised solely for efficiency but should also factor in multiple other vital aspects such as flexibility and resilience. The COVID-19 crisis illustrated the limits of just-in-time supply chains, with optimisation for efficiency contributing to shortages in essential food and hygiene items. In practice, computing models are optimised for a reward function. In the context of net zero, this reward function should not only reflect the objective to reduce emissions but also additional goals such as resilience.

Unexpected events could also disrupt the digital infrastructure, and redundancy in the system is a way to increase adaptability and resilience. An example of such redundancy is the Galileo constellation of European satellites, which could provide resilience in the event of an interruption affecting the US-based Global Positioning System (GPS). Such redundancy might not necessarily protect the digital infrastructure against solar storms, low probability events that might in future disrupt electrical and electronic systems on a large scale. A world with digital control systems will require further fail-safe mechanisms that could cope with global perturbations.

Verification and robustness

In many applications – especially safety-critical applications – the quality of the decisions or predictions made by digital systems needs to be verifiable to a high standard, and systems need to be robust enough so that predictions are not thrown by small perturbations or other noise. Verification and robustness of data-driven systems involved in control loops for the planet is important due to the potential impact of perturbations to these systems; although in some cases this issue may be resolved through building redundancy in the system.

For example, when using machine learning, small changes to a system can be quickly replicated and deployed, with effects at a large-scale[164]. This is important in the context of digital technology for the planet, because applications such as autonomous vehicles and smart electricity grids will require AI and other digital systems with high levels of precision and control. Truly safety critical AI systems are still at the research phase, but autonomous AI control systems were successfully implemented and operate with minimum supervision to regulate the heating and cooling of data centres, providing an example of development of a safe autonomous system (see next chapter's Box 12).

162. House of Commons Science and Technology Committee 2011 Scientific advice and evidence in emergencies (see https://publications.parliament.uk/pa/cm201011/cmselect/cmsctech/498/498.pdf, accessed 16 October 2020)
163. The Royal Academy of Engineering 2013 Extreme space weather: impacts on engineered systems and infrastructure (see https://www.raeng.org.uk/publications/reports/space-weather-full-report, accessed 16 October 2020)
164. *Op. Cit.* 12

Recommendations

For digital technologies deployed in the context of net zero to work for everyone, they will need to enable individuals and society to scrutinise their outputs and methods, they must be secure and resilient, and there must be a wide engagement of all stakeholders.

RECOMMENDATION 3

The UK Government, through a taskforce set up to connect and amplify cross-departmental and cross-sector initiatives on the digitalisation of the net zero transition, should enable industry, in particular the larger tech companies, as well as regulators and the third sector to ensure:

- Data-driven systems for net zero be developed to allow people to inspect and challenge their output. There should be a concerted effort to set standards to support contestation: data-driven systems to achieve net zero should be explainable, transparent, and auditable.
- Digital systems for net zero be developed to be secure and resilient. A collaborative effort should set resilience standards for data-driven systems deployed to achieve net zero: they should be able to work on a range of scales, be cybersecure, interoperable, flexible, safe and robust.
- Digital systems benefit the communities into which they are deployed. A collaborative effort should involve affected communities in order to develop a shared understanding of the purpose of technologies deployed in the context of net zero and to co-design approaches to navigate the associated dilemmas. This requires careful design of the interface between people and technology, and consideration of the societal impact of such technologies. Participatory design should play a central role in shaping and delivering digital solutions to the net zero challenge.

Chapter four
Green computing

Left

Green computing

Studies reported a wide range of estimates of digital technology's contribution to global emissions, varying from 1.4% to 5.9%.

Digital technologies rely on a complex infrastructure of cables, fibres, computers, data centres, routers, servers, repeaters, satellites, radio masts and energy needed to perform their functions. Building and operating these systems requires energy, and – if computing systems are to be widely deployed as digital infrastructure for managing activities across sectors – the energy demands and emissions from them will need to be understood and managed. The digital infrastructure is growing, as is demand for computing. While recent attempts to estimate the carbon footprint of the Internet have prompted headlines about how many emissions are generated with each daily digital interaction, there is a range of such estimates, and it can be challenging to calculate the extent to which emissions from digital technologies present a challenge to overall efforts to achieve net zero. The development of data-driven systems that truly contribute to net zero will require better evidence and guidance about their own footprints including all Scopes, and their energy proportionality, as well as new approaches to lower their energy consumption and towards greater integration of renewable energy sources.

The evidence about the emissions and energy use of digital systems is limited

Understanding emissions from digital technology

Recent years have seen growing interest in the amount of carbon generated by digital technologies and the extent to which this poses a threat to sustainability efforts. While attracting significant media attention, studies in this area have presented a range of different estimates of the contributions to global emissions made by digital technologies, with these varying from 1.4% to 5.9% of global greenhouse gas emissions[165–168]. As a comparison, maritime transport is responsible for about 2.5% of global emissions[169].

Estimating the carbon footprint of digital technology is an intricate challenge, with studies choosing different boundary conditions – it is arguable whether the carbon footprint should include, for example, the emissions resulting from the economic activity that digital technology enables, or the emissions that it saves in other sectors. Estimating the energy demand of digital technology is a more tractable problem, and therefore most of the chapter considers the electricity demand of the tech sector, rather than its emissions. Key questions to consider include how energy is used, how much is used, and how it can be controlled.

165. Andrae ASG and Edler T 2015 On global electricity usage of communication technology: trends to 2030. Challenges, 6(1), 117-157. (see https://www.mdpi.com/2078-1547/6/1/117/html, accessed 16 October 2020)
166. Andrae ASG 2020 New perspectives on internet electricity use in 2030. Eng. Appl. Sci. Lett. 2020, 3(2), 19-31. (see https://www.researchgate.net/profile/Anders_Andrae/publication/342643762_New_perspectives_on_internet_electricity_use_in_2030/links/5efe34a3299bf18816fb82eb/New-perspectives-on-internet-electricity-use-in-2030.pdf, accessed 16 October 2020)
167. Malmodin J and Lunden D 2018 The Energy and Carbon Footprint of the Global ICT and E&M Sectors 2010–2015. Sustainability 2018, 10(9), 3027 (see www.mdpi.com/2071-1050/10/9/3027, accessed 16 October 2020)
168. Belkhir L and Elmeligi A 2018 Assessing ICT global emissions footprint: Trends to 2040 & recommendations. Journal of Cleaner Production, 177, 448-463. (see https://www.electronicsilentspring.com/wp-content/uploads/2015/02/ICT-Global-Emissions-Footprint-Online-version.pdf, accessed 16 October 2020)
169. See https://www.imo.org/en/OurWork/Environment/Pages/Greenhouse-Gas-Studies-2014.aspx, accessed 25 November 2020

Emissions from the manufacture and life-cycle of digital technology

Studies estimate that emissions from digital technologies come in large part (around two thirds) from the electricity they consume whilst in use, and in smaller but still substantial part from 'embodied' emissions incurred during the life-cycle of these technologies, from raw materials extraction, through to manufacturing, distribution, end-of-use recycling and disposal of materials[170]. When considering user devices only, such as smartphones and laptops, the share of embodied emissions reaches approximately 50%. The reason is, compared with networks and servers, user devices consume less power in their use phase, as they are only used for parts of the day, but they are replaced often, especially smartphones.

Variations in estimates of the carbon footprint of digital technologies can be explained in part by the different boundary conditions set by different studies. For example, studies variably include estimates of emissions from the generation of acquired and consumed electricity (Scope 2 emissions) and those arising upstream in the supply chain as well as downstream (Scope 3 emissions). A number of tech companies have realised the scale of the issue and taken steps towards circularising the tech industry, meaning they pledged to reuse equipment and generate less waste – for example Google partnered with the Ellen MacArthur Foundation to circularise its business[171]; Fairphone produces modular mobile phones with recyclable parts[172]. One of the largest technology renewal centres in the world is run by HPE in Erskine, Scotland[173]. All tech companies and manufacturers need to further promote and implement best practice towards reducing the emissions associated with the manufacture of digital technology. Individuals also have a part to play (see Box 10), as well as policy: for example, the European Commission facilitated an agreement among major mobile phones manufacturers to adopt a common charger with micro-USB connectors, thus reducing e-waste (see Box 11).

Energy used during computing

Energy demands from the operation of digital technology come from both the power consumption of local devices and from the electricity needs of infrastructures underpinning the internet – networks and data centres. Data transmission networks represented about 1% of global electricity use in 2019 (around 250 TWh), with mobile networks accounting for two-thirds of this 1%[174].

Considering user devices only, such as smartphones and laptops, the share of embodied emissions reaches approximately 50%.

170. *Op. Cit.* 167

171. Google 2019 A circular Google (see https://services.google.com/fh/files/misc/circular-google.pdf, accessed 16 October 2020)

172. See https://www.fairphone.com/en/ (accessed 16 October 2020)

173. Financial Times 2019 Giving old tech a second life (see https://www.ft.com/content/990c7846-e5cf-11e9-9743-db5a370481bc, accessed 16 October 2020)

174. See https://www.iea.org/reports/data-centres-and-data-transmission-networks#recommended-actions (accessed 16 October 2020)

While global internet traffic increased on average 30% a year, the energy demand of data centres has hardly increased over the past decade.

Data centres, where most of the servers of the planet are concentrated, host internet platforms and process and store much of the data generated in everyday activities. These centres account for a large proportion of the electricity consumption from computing. Global data centre electricity demand in 2019 was estimated to be around 200 TWh, or around 0.8% of global electricity demand[175,176]. This estimate seems to converge with a previous study[177], and departs from others[178,179], which relied on somewhat older data and were based on historical trends that likely no longer apply[180], such as the assumed exponential growth of energy consumption by data centre and networks. The energy demand of data centres has remained more or less constant over the past decade, while data centre workloads has kept on rising and compute power has gone up considerably, with global internet traffic increasing on average 30% every year[181].

To achieve net zero, the tech sector, alongside most other sectors of the economy, will need to achieve actual zero emissions, rather than resort to offsetting schemes[182]. There are already examples of companies and collaborative initiatives that are setting voluntary efficiency and emissions targets. In February 2020, the tech and telecommunications industry agreed a target to reduce greenhouse gas emissions by 45% between 2020 and 2030[183]. Tech giants have recently made bold pledges about their respective carbon footprints (see Box 12)[184 – 188].

However, assessing the progress of the sector towards these targets will require access to good quality, reliable data about its emissions and energy use. The relatively few studies available about the energy consumption of digital systems reveal variations in the sources of data used, with some studies relying on private, unpublished data. For example, life-cycle analysis data about digital products is currently not freely available in most cases. The tech sector needs to improve data collection and reporting practice about the energy consumption of digital systems, as well as sources and energy mix, to monitor and accelerate progress against climate targets. Interventions will need to manage the fact that the digital infrastructure is global, with only a few data centres from large tech companies currently located in the UK. In addition to informing policy decisions, making such data available would increase understanding of the components of energy use, as well as how they can be reduced and the system optimised.

175. *Op. Cit.* 174
176. Masanet *et al* 2020 Recalibrating global data center energy-use estimates. Science 367, 6481. (see https://www.gwern.net/docs/cs/2020-masanet.pdf, accessed 16 October 2020)
177. *Op. Cit.* 167
178. *Op. Cit.* 165
179. *Op. Cit.* 168
180. *Op. Cit.* 166
181. *Op. Cit.* 174
182. Climate Change Committee 2019 Net Zero – The UK's contribution to stopping global warming (see https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/, accessed 16 October 2020)
183. See https://www.itu.int/en/mediacentre/Pages/PR04-2020-ICT-industry-to-reduce-greenhouse-gas-emissions-by-45-percent-by-2030.aspx (accessed 16 October 2020)
184. See https://sustainability.aboutamazon.com/about/the-climate-pledge (accessed 16 October 2020)
185. See https://blogs.microsoft.com/blog/2020/01/16/microsoft-will-be-carbon-negative-by-2030/ (accessed 16 October 2020)
186. See https://www.apple.com/uk/newsroom/2020/07/apple-commits-to-be-100-percent-carbon-neutral-for-its-supply-chain-and-products-by-2030/ (accessed 16 October 2020)
187. See https://blog.google/outreach-initiatives/sustainability/our-third-decade-climate-action-realizing-carbon-free-future/ (accessed 16 October 2020)
188. See https://sustainability.fb.com/ (accessed 16 October 2020)

BOX 10

Example actions individuals can take to reduce emissions from the tech they use.

A number of news articles have warned about the emissions from the internet, and it can be confusing for individuals to know what they should make of it[189]. Everyone has the power to change the way they use digital technology in their daily lives. Here are a few simple actions everyone can take.

Using devices for longer: using phones, laptops, tablets and smart TVs for longer can reduce emissions. People tend to change their mobile phones every other year or so[190], partly motivated by phone contracts that offer the newest models at advantageous costs. However, there is evidence that people are increasingly using their smartphones for longer[191]. Embodied emissions for a mobile phone kept two years represent about half of all the emissions it will generate through its lifetime. Keeping phones for twice as long can significantly reduce this share of emissions. Protecting and repairing phones is good practice to help keep them longer. Getting a phone or other device second-hand, or passing it on, and sharing equipment are other ways to reduce the share of embodied emissions associated with devices.

Recycling old devices: although refurbishing or repurposing a device should be considered first (see above), recycling old devices will also help reduce resource use and electronic waste. Old phones kept in a drawer at home amount to a form of landfill. Recycling a device will help repurpose materials, and save emissions and environmental damage linked with the exploitation of natural resources. For example, there is 100 times more gold in a tonne of e-waste than in a tonne of gold ore[192]. The Recycle Your Electricals campaign[193] can help locate nearest recycling points throughout the UK.

Streaming responsibly: avoiding streaming unnecessarily high-resolution or unnecessary content would help save emissions. Streaming one hour on a smartphone generates roughly 8 times more emissions in 4K or UHD (Ultra High Definition) compared with SD (Standard Definition)[194], while users may not be able to see any difference on small screens. Arguably decisions on limiting streaming resolution should be taken by platforms and regulators. Responsible streaming would be supported by changes in online services design, such as turning off the video for a large portion of YouTube users who are only listening to the content – a study showed this could save between 1% and 5% of the service's total emissions, a reduction comparable to what is achieved with running Youtube's servers on renewable energy[195].

189. Rice A and Friday A 2020 Internet emissions: what's the issue? (see https://royalsociety.org/blog/2020/05/internet-emissions-whats-the-issue/, accessed 16 October 2020)
190. *Op. Cit.* 168
191. CNBC 2019 Smartphone users are waiting longer before upgrading — here's why (see https://www.cnbc.com/2019/05/17/smartphone-users-are-waiting-longer-before-upgrading-heres-why.html, accessed 16 October 2020)
192. Platform for Accelerating the Circular Economy and World Economic Forum 2019 A New Circular Vision for Electronics Time for a Global Reboot (see http://www3.weforum.org/docs/WEF_A_New_Circular_Vision_for_Electronics.pdf, accessed 16 October 2020)
193. See recycleyourelectricals.org.uk (accessed 16 October 2020)
194. Calculator available on the International Energy Agency website https://www.iea.org/commentaries/the-carbon-footprint-of-streaming-video-fact-checking-the-headlines (accessed 16 October 2020)
195. Preist C *et al* 2019 Evaluating Sustainable Interaction Design of Digital Services: The Case of YouTube. in Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems. https://research-information.bris.ac.uk/ws/portalfiles/portal/184369887/Preist_chi2019.pdf, accessed 16 October 2020)

The energy consumption of digital technologies can be controlled in several ways

A range of technology advances have enabled data services to continue growing, whilst the energy consumption of data centres has kept constant. Promising new research directions point to ways in which the energy demands from digital systems could be further reduced, as demand for their use continues to rise. Changes to personal behaviours is one of the market forces that can shape this demand (Box 10).

BOX 11

Example policy intervention: mobile phone charger standardisation.

In the late 2000s and early 2010s, mobile phone chargers were only compatible with specific mobile phones. The chargers used often varied according to the manufacturer and model; and more than thirty different types of charger were on the market. Apart from causing inconvenience to the consumer, this created unnecessary electronic waste. Mobile phone chargers are responsible for around 11,000 - 13,000 tonnes of e-waste per year in the EU, and associated life cycle emissions of around 600 - 900 kt CO_2e.

The European Commission facilitated an agreement among major handset manufacturers to adopt a common charger for data-enabled mobile phones sold in the EU. In June 2009, a Memorandum of Understanding (MoU) was signed in which mobile phone manufacturers agreed to harmonise chargers for new models of data-enabled handsets, coming onto the market as of 2011. As a result, major mobile phone manufacturers agreed to adopt a universal charger for data-enabled mobile phones sold on the European market. The MoU committed the industry to provide charger compatibility on the basis of the micro-USB connector. The MoU expired at the end of 2012 but it has effectively been extended by a number of its signatories through two subsequent 'letters of intent', signed in 2013 and 2014.

A 2019 study examined the impact of the policy. Over the years there has been a convergence of around three quarters of the market to micro-USB chargers. The remainder of the market – essentially corresponding to Apple's iPhones – has continued to rely on proprietary connectors. This is allowed under the terms of the MoU as long as adaptors continue to be available on the market. Despite harmonisation, the electrical power supply element of chargers can still vary in charging speed, although nearly all modern chargers are compatible with almost all phones with a micro-USB connector.

The fact that a high proportion of consumers owns a mobile phone means that phones can influence the market for other devices. It is already relatively common for small electronic devices, such as action cameras and wearables, to be sold with a cable but without an electrical power supply; this is based partly on the assumption that individuals will be able to use their mobile phone chargers. The adoption of a common connector or electrical power supply across all mobile phones could therefore could also be expected to contribute to a greater adoption of this in other devices in which this makes technological, practical and commercial sense.

Currently, there is no voluntary or regulatory requirements as regards the interoperability for either mobile phones or other portable electronic devices.

Extracts adapted from https://ec.europa.eu/growth/sectors/electrical-engineering/red-directive/common-charger_en and https://op.europa.eu/en/web/eu-law-and-publications/publication-detail/-/publication/c6fadfea-4641-11ea-b81b-01aa75ed71a1 (accessed 16 October 2020)

Energy-efficient computing

Digital technology equipment has become increasingly energy-efficient. Progress in hardware has meant that the number of transistors in a dense integrated circuit has doubled about every other year, an empirical observation known as Moore's law. This has allowed the telecommunications and tech industry to exponentially increase chips' performance and speed without corresponding increases in their power consumption.

Several studies acknowledge that Moore's law has slowed down over the past decade, although there is delay between observations of this effect and its impact outside of research labs which means efficiencies might be continuing. Research into new types of low power processors is needed to continue to push the limit of hardware energy-efficiency. Recent developments include brain-inspired neuromorphic hardware[196] and new AI accelerator chips, such as Apple's A14 chip, which claims to achieve 10 times faster machine learning calculations[197].

Data centre management

Organisations have achieved further energy efficiencies in data infrastructures by moving their data storage and processing from local servers to the public cloud, ie in remote data centres, although a large proportion of computing still happens within enterprise servers – smaller, non-centralised servers[198]. Data centre management can reduce emissions in several ways[199].

Moving computing to the cloud has allowed more efficient patterns of server use[200]. Centralisation of these servers allows more effective management, with the servers' load being optimised so that they do not consume energy while idle. Illustrating the scale of the issue, a 2017 survey of 16,000 enterprise servers revealed that a quarter of them were entirely idle, consuming energy but performing no useful computing operation[201]. However, the best on-premise data centres can be currently as good as the average public cloud provider, with utilisation levels on the cloud reaching only 40% on average versus 30% on-premises – suggesting there is significant room for improvements[202].

Server virtualisation, a technique that involves partitioning a physical server into multiple virtual machines, has also enabled data centre operators to deliver greater output with fewer servers. This means that data centres can run with fewer servers, which reduces the risk of overheating in the facility and improves energy efficiency. However, server virtualisation should be done in combination with effective ways to monitor and regulate server load, otherwise virtual machines also risk ending up idle.

Moving computing to the cloud has allowed more efficient patterns of server use.

196. Blouw P *et al* 2019 Benchmarking Keyword Spotting Efficiency on Neuromorphic Hardware. In Proceedings of the 7th Annual Neuro-inspired Computational Elements Workshop (NICE '19). Association for Computing Machinery, New York, NY, USA, Article 1, 1–8. (see https://arxiv.org/abs/1812.01739v2, accessed 16 October 2020)
197. See https://www.apple.com/uk/newsroom/2020/09/apple-unveils-all-new-ipad-air-with-a14-bionic-apples-most-advanced-chip/ (accessed 16 October 2020)
198. Uptime Institute 2020 Data Center Industry Survey Results (see https://uptimeinstitute.com/2020-data-center-industry-survey-results, accessed 16 October 2020)
199. *Op. Cit.* 176
200. European Commission Joint Research Centre 2020 Best Practice Guidelines for the EU Code of Conduct on Data Centre Energy Efficiency (see https://e3p.jrc.ec.europa.eu/publications/2020-best-practice-guidelines-eu-code-conduct-data-centre-energy-efficiency, accessed 16 October 2020)
201. Koomey J and Taylor T 2017 Zombie/comatose servers redux (see https://www.anthesisgroup.com/report-zombie-and-comatose-servers-redux-jon-taylor-and-jonathan-koomey/, accessed 16 October 2020)
202. Uptime Institute 2020 Beyond PUE: Tackling IT's Wasted Terawatts (see https://uptimeinstitute.com/beyond-pue-tackling-it%E2%80%99s-wasted-terawatts, accessed 16 October 2020)

BOX 12

Examples of tech industry best practice towards decarbonisation.

Climate pledge: Microsoft and supply chain to be carbon negative by 2030

One of the most ambitious climate pledges in the tech sector so far comes from Microsoft, who announced that by 2030 they would be carbon negative, and by 2050 they would remove from the environment all the carbon the company has emitted either directly or by electrical consumption since it was founded in 1975[203]. Importantly, the pledge to become carbon negative by 2030 includes supply chain emissions (Scope 3), which represent a large share of the company's emissions. For 2020, Microsoft expects to emit 100,000 metric tons of Scope 1 carbon, four million tons of Scope 2 carbon, and 12 million tons of Scope 3.

To become carbon negative by 2030, Microsoft pledges to reduce emissions across its business by more than half, and plans to remove more carbon than it emits annually as a company. In support of this, Microsoft announced a $1bn Climate Innovation Fund to accelerate the global development of carbon reduction, capture, and removal technologies. To incentivise change across all part of its business, Microsoft has an internal carbon tax introduced in 2012, increased to $15 per metric ton of carbon in 2019, and expanded from Scope 1 to Scope 2 and 3 in 2020. From 2021, the company is also planning to make carbon reduction an explicit aspect of its supply chain procurement processes.

Data centre management: Google-Deepmind's use of AI for the cooling of data centres

Data centres, facilities comprising of rows upon rows of servers, generate a lot of heat. Over the last decade there have been a number of improvements in making the cooling of data centres more energy efficient. In 2016, Deepmind achieved a step change using machine learning and AI systems to manage the cooling of Google's data centres, helping save up to 40% of the energy needed for cooling[204]. To achieve this, Deepmind researchers used historical data from a data centre – such as temperature, power, pump speeds, etc – to train an ensemble of deep neural networks[205]. In doing so, they trained the neural networks to optimise the ratio of the total building energy usage to the IT energy usage (also known as Power Usage Effectiveness, or PUE).

Google then successfully implemented AI control systems that can operate with minimum supervision to regulate the heating and cooling of its data centres[206]. It achieved this level of autonomy by constraining the system's optimisation boundaries to a narrower operating regime, thus prioritising safety and reliability. These Autonomous AI control systems are able to learn from data and improve over time. They came up with unexpected solutions such as taking advantage of winter conditions to produce colder than usual water.

203. *Op. Cit.* 164 (Microsoft pledge)

204. Gamble C and Gao J 2018 Safety-first AI for autonomous data centre cooling and industrial control (see https://deepmind.com/blog/article/safety-first-ai-autonomous-data-centre-cooling-and-industrial-control, accessed 16 October 2020)

205. Evans R and Gao J 2016 DeepMind AI reduces energy used for cooling Google data centers by 40% (see https://blog.google/topics/environment/deepmind-ai-reduces-energy-used-for/, accessed 16 October 2020)

206. Google 2019 Environmental report (see https://services.google.com/fh/files/misc/google_2019-environmental-report.pdf, accessed 16 October 2020)

Image
The Dalles Google Data Center.

The world's most powerful and efficient supercomputer

The world's most powerful supercomputer is also world-leading in terms of energy-efficiency, and it was set up to deliver societal value. Based at the RIKEN Center for Computational Science in Kobe, Japan, the Arm-based Fujitsu Fugaku was developed to address high-priority social and scientific issues, part of Japan's Society 5.0 plan[207]. The computer is due to begin full operation in 2021, with a breadth of areas of application including weather and climate forecasting; energy creation, storage and use; the development of clean energy; and new materials development.

The Arm-powered supercomputer ranked as the most efficient in the world in November 2019, achieving 16.9 GFlops/Watt power-efficiency[208]. In June 2020, it also became the world's most powerful supercomputer, delivering 415.5 petaflops, i.e. 2.8x more than the second-most powerful supercomputer, IBM's Summit, using the same benchmark[209]. Fugaku's reported peak performance is over 1,000 petaflops (1 exaflops).

207. See https://www.riken.jp/en/news_pubs/news/2020/20200623_1/ (accessed 16 October 2020)
208. See https://www.top500.org/lists/green500/2019/11/ (accessed 16 October 2020)
209. See https://www.top500.org/news/japan-captures-top500-crown-arm-powered-supercomputer/ (accessed 16 October 2020)

For any computing application, its cost in terms of energy consumption and emissions should be weighed against its benefits.

Data centre cooling technologies have employed new mechanisms of heat exchange and contributed energy savings. To reduce the cost of cooling, data centres can be immersed, either underwater or in tanks filled with fluids with high cooling power[210,211]. Machine learning and AI systems have also helped efficiently manage the cooling of data centres, saving up to 40% of the energy needed for cooling servers (see Box 12).

Improvements in data storage drives have allowed faster, more energy-efficient processing. Solid-state drives allow a faster exchange of data with the main processor which makes the system higher performing.

The sector is also seeing a move towards larger data centres, or hyperscale data centres, that are more energy efficient. These hyperscale data centres allow efficiencies of scale and make investments in the development of AI systems to optimise energy use more cost-efficient.

The net emissions from digital technologies depend on how these technologies are used

Digital technologies have enabled the creation of new services, with contributions both positive and negative in terms of emissions across sectors (see chapter 1). For this reason, giving an estimate of the carbon footprint of digital technology risks being inaccurate and misleading. It is not their use that will determine the overall carbon footprint of these technologies, but how they are used that will determine their overall impact.

Energy proportionality

For any data and computing application or task, but perhaps particularly for those tasks that are highly compute-intensive, its cost in terms of energy consumption should be weighed against its benefits. When assessing energy proportionality, it is important to consider greenhouse gas emissions and savings in all three Scopes. Achieving more useful work for less energy can contribute to making a digital system more energy proportionate than another (saving Scope 1 emissions). Relying on cleaner energy can make a system more energy proportionate (saving Scope 2 emissions). Minimising the turnover of the infrastructure and its embodied emissions also affects whether a system is more energy proportionate (saving Scope 3 emissions). In some cases the most energy proportionate solution might not be the one realising the most efficiency at Scope 1, if contributions at Scope 2 and Scope 3 make a bigger difference overall.

Software engineers could also be encouraged to take into account the emissions from code and applications. They should consider whether there might be leaner code that could achieve the same outcome with fewer emissions; and the implication of this for when an application is run at scale. A framework for assessing whether a computing application justifies the energy incurred should include questions such as: Overall, is this application energy proportionate? Does the application justify the use of large amounts of data and computing power? Are there more energy-efficient algorithms available or altogether better ways to achieve the same result?

210. BBC 2020 Microsoft's underwater data centre resurfaces after two years (see https://www.bbc.co.uk/news/technology-54146718, accessed 16 October 2020)

211. CSMA 2019 Case study: Submer, Immersion Cooling for Research and Colocation (see https://www.gsma.com/futurenetworks/wiki/submer-immersion-cooling/

Specific applications of digital technologies might require particular attention. For example, Bitcoin, a widely used cryptocurrency, consumed an estimated 50 – 70 TWh of electricity in 2019, or 0.2 – 0.3% of global electricity use (see Box 13)[212]. This is because Bitcoin uses a form of blockchain based on extremely energy-inefficient 'Proof-of-Works' algorithms. There are other forms of blockchain technologies available that have incorporated newer, more energy-efficient algorithms, which could be developed and used towards some of the applications for net zero described in this report.

Bitcoin provides an example of use of technology that is not energy proportionate, which should be used as part of foresight, when considering other potential technology applications and associated externalities. It illustrates how rebounds can happen, with the technology driving Bitcoin mining, the manufacture, purchase and disposal of specialist hardware, and an escalation in energy use.

Supercomputer systems, often referred to as exascale computing[213] systems, are also anticipated to enable advances in many application domains, such as climate mitigation and adaptation. Based on technology available ten years ago, scaling systems to an exaflop level would have consumed more than a gigawatt of power, roughly the output of 400 onshore wind turbines[214]. But supercomputers have developed to consume less energy. The world's most powerful supercomputer in the world in June 2020, the Arm-based Fujitsu Fugaku, had a reported peak power consumption of 30 MWatt of electricity, roughly the output of 12 onshore wind turbines (see Box 12).

It is often said quantum computing, an emerging form of computing harnessing quantum mechanics, promises a step-change in the complexity and rapidity of calculations, well beyond those of conventional computers. New developments could mean that the technology might become more energy efficient than conventional supercomputers in the long run[215,216]. However, quantum computers are still in their infancy and highly unlikely to become widely used in the decades leading to 2050. So far, their operation has been limited and impractical, requiring the cooling of their circuits to ultra-low temperatures, which has a very high energy cost.

While computing infrastructure can make use of renewables, the continued expansion of renewable power assets will take time and capital. This reinforces the need for energy proportionate computing.

212. *Op. Cit.* 174

213. Exascale computing refers to computing systems capable of at least one exaFLOPS, or a billion billion calculations per second.

214. U.S. Department of Energy Office of Science 2010 The Opportunities and Challenges of Exascale Computing (see https://science.osti.gov/-/media/ascr/ascac/pdf/reports/Exascale_subcommittee_report.pdf, accessed 16 October 2020)

215. Forbes 2020 The Largest Roadblock In Quantum Computing Has Been Passed (see https://www.forbes.com/sites/kevinanderton/2020/04/20/the-largest-roadblock-in-quantum-computing-has-been-passed-infographic/#2735a0755a08, accessed 16 October 2020)

216. Physics World 2020 Quantum computers vastly outperform supercomputers when it comes to energy efficiency (see https://physicsworld.com/a/quantum-computers-vastly-outperform-supercomputers-when-it-comes-to-energy-efficiency/, accessed 16 October 2020)

BOX 13

Bitcoin, an energy intensive cryptocurrency.

Cryptocurrencies are the most popular application for blockchain to date, and Bitcoin represents the biggest market share of all cryptocurrencies. Since its inception in 2008, Bitcoin's energy demand has grown rapidly. It consumed an estimated 50-70 TWh of electricity in 2019, or 0.2 – 0.3% of global electricity use – in the order of two years of Scotland's electricity consumption[217].

Bitcoin uses an immutable ledger, or blockchain, to record transactions. In the process of recording transactions, it uses a 'Proof of Work' algorithm to validate them. Transactions are proven through complicated mathematical operations, the validity of which can be verified by any network users. The users solving the problem are called Bitcoin 'miners', and get a reward for doing so in the form of Bitcoins. Each time a block is added to the blockchain the computing task becomes harder, as the number of users involved grows, and the load on the network becomes greater.

In addition, the Bitcoin protocol is regularly recalibrated in order to ensure that new 'coins' cannot be minted too quickly, by increasing the difficulty of the mathematical operations to solve.

As a result, Bitcoin miners regularly upgrade their servers to keep up with the mining race. The global e-waste associated with the replacement of Bitcoin mining machines was estimated at about 11k metric tons per year (comparable to Luxembourg's at 12 kt) assuming Koomey's Law – which states that the energy efficiency of computers doubles roughly every 18 months[218,219].

The increase in computing power also means more electricity gets consumed. A lot of Bitcoin mining happens where electricity is cheap. The Sichuan region in China is reported to support nearly half of global Bitcoin mining capacity, and hydropower varies with seasons in the region, which means that Bitcoin mining must draw on traditional electricity generation such as coal[220].

Not all cryptocurrencies use the 'Proof of Work' algorithm. There are several alternatives that are more energy-efficient, one of the most commonly used being 'Proof of Stake' – where new blocks are not added by a user solving computationally intensive puzzles, but by a user chosen via various combinations of random selection and wealth or age (the stake).

217. See Cambridge Centre for Alternative Finance https://www.cbeci.org/ (accessed 16 October 2020)

218. de Vries A 2019 Renewable Energy Will Not Solve Bitcoin's Sustainability Problem. Joule, 3(4), 893-898. (see https://doi.org/10.1016/j.joule.2019.02.007, accessed 16 October 2020)

219. Koomey JG *et al* 2011 Web Extra Appendix: Implications of Historical Trends in the Electrical Efficiency of Computing. IEEE Annals of the History of Computing, 33(3), S1-S30. (see https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.323.9505&rep=rep1&type=pdf, accessed 16 October 2020)

220. Bendiksen C *et al* 2018 The Bitcoin Mining Network: Trends, Composition, Marginal Creation Cost, Electricity Consumption & Sources. CoinShares Research. (see https://coinshares.com/assets/resources/Research/bitcoin-mining-network-november-2018.pdf, accessed 16 October 2020)

Computing can run on clean energy and enable greater grid integration

Evidence suggests the uptake of renewable energy has, so far, effectively helped reduce emissions from digital technology use. Many major Internet companies, including Google, Microsoft, Facebook and Amazon, claim to run their data centres using renewable energy where they can, or buying it elsewhere to compensate for sites where they cannot. The top four corporate off-takers[221] of renewables in 2019 were all digital technology companies, led by Google[222]. In 2018, Google (10 TWh)[223] and Apple (1.3 TWh)[224] purchased or generated enough renewable electricity to match 100% of their data centre energy consumption. Amazon and Microsoft sourced about half of their data centre electricity from renewables[225,226]. To incentivise company-wide uptake of renewables, Microsoft has developed an internal 'carbon pricing' mechanism (see Box 12).

However, not all forms of renewable energy uptake guarantee cuts in emissions[227]. The impact on emissions depends on the type of renewable energy companies use (e.g. biofuels, solar, wind, hydropower), and the proportion of their renewable energy coming from on-site renewable electricity generation, Power Purchasing Agreements (PPAs) and Renewables Obligation Certificates (ROCs, or Renewable Energy Certificates in the US). PPAs ensure additional renewable energy is effectively generated and fed into the grid, but there are a range of ROCs which do not guarantee this. Companies making pledges to be 100% renewable should source all of their energy through on-site renewables, PPAs or investment in off-site renewable projects.

There is an opportunity for another approach that can increase the use of renewables, and thus contribute to decarbonising electricity grids: scheduling. This means managing the timing of computing so jobs that are not time-sensitive are done when there is lower overall demand or more renewable supply. This spreads computing jobs across peaks. There are already examples[228]. As part of a commitment to '24x7 carbon-free energy', Google has recently announced a new intelligent computing platform that allocates tasks to time when renewable energy generation peaks[229]. In support of such practice, mechanisms could be devised to strongly incentivise purchasers to contribute to solving the intermittency problem of renewable power generation.

Evidence suggests the uptake of renewable energy has, so far, effectively helped reduce emissions from digital technology use.

221. An off-taker is a purchaser of renewable energy through a power purchase agreement (PPA). PPAs are contracts between the owner of a renewable energy plant and the end-consuming off-taker.

222. *Op. Cit.* 174

223. *Op. Cit.* 206

224. Apple 2019 Environmental responsibility report (see https://www.apple.com/environment/pdf/Apple_Environmental_Responsibility_Report_2019.pdf, accessed 16 October 2020)

225. See https://sustainability.aboutamazon.com/sustainability-in-the-cloud (accessed 16 October 2020)

226. Microsoft 2019 We're increasing our carbon fee as we double down on sustainability (see https://blogs.microsoft.com/on-the-issues/2019/04/15/were-increasing-our-carbon-fee-as-we-double-down-on-sustainability/, accessed 16 October 2020)

227. Financial Times 2019 Why '100% renewable energy' pledges are not enough (see https://www.ft.com/content/d75f49d0-103f-11ea-a225-db2f231cfeae, accessed 16 October 2020)

228. Grange L *et al* 2018 Green IT scheduling for data center powered with renewable energy. Future Generation Computer Systems, Elsevier, 86, 99-120. (see https://oatao.univ-toulouse.fr/22386/1/grange_22386.pdf, accessed 16 October 2020)

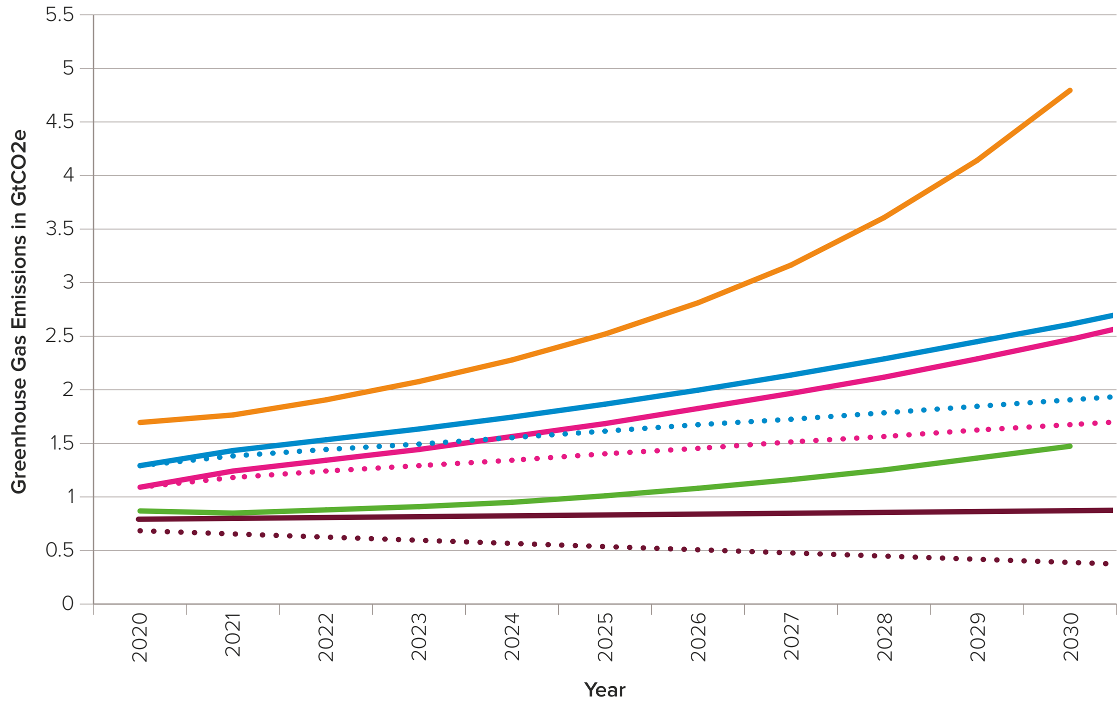
229. *Op. Cit.* 41

FIGURE 5

Projections of the emissions from digital systems to 2030, and 1.5°C trajectory agreed by the tech and telecommunications industry[230 – 232]. These published projections depend in part on assumptions on the energy mix and decarbonisation of the sector. Note that these projections relied on somewhat old data and were based on historical trends that likely no longer apply[233], such as the assumed exponential growth of energy consumption by data centre and networks. Belkhir and Elmeligi (2018) proposed at the time that their linear growth scenarios reflect the impact that mitigating actions could have between now and 2040. Andrae and Edler (2015) mentioned a worst case scenario which is not shown here as the authors' more recent publications ruled it out, on the ground that digital technology has achieved greater efficiencies improvements since[234]. An analysis by the International Telecommunication Union proposed a possible '1.5°C trajectory', involving greater decarbonisation of energy supply[235].

KEY

- Belkhir & Elmeligi (2018) – Maximum exponential
- Belkhir & Elmeligi (2018) – Maximum linear
- Belkhir & Elmeligi (2018) – Minimum exponential
- Belkhir & Elmeligi (2018) – Minimum linear
- Andrae & Edler (2015) – Expected case
- Andrae & Edler (2015) – Best case
- ITU L.1470 – unchanged electricity emission
- ITU L.1470 – 1.5°C trajectory



230. *Op. Cit.* 165
231. *Op. Cit.* 168
232. International Telecommunication Union 2020 Recommendation ITU-T L.1470: Greenhouse gas emissions trajectories for the information and communication technology sector compatible with the UNFCCC Paris Agreement (see https://www.itu.int/ITU-T/recommendations/rec.aspx?rec=14084, accessed 30 October 2020)
233. *Op. Cit.* 166
234. *Op. Cit.* 166
235. *Op. Cit.* 232

Conclusions

The energy demands of computing could develop in different ways, and projections of future emissions vary widely (see Figure 5) – greater data availability and a continued analysis of underlying drivers of change will be necessary to produce reliable projections in future, and to drive decarbonisation. If gains in energy-efficiency and demand for computing both reach a plateau then computing's power consumption will stabilise. However, if demand for computing increases more than the efficiency gains in digital technology, then energy demand will go up.

To achieve the vision of digital technology harnessed for the good of the planet set out in chapter 1, the use of data and digital technologies will need to expand – with new applications and services across sectors. If this vision is to be achieved without computing becoming an increasing proportion of global energy use and emissions, action will be needed to:

- develop and deploy the applications described in chapter 1, to enable emission reductions across sectors;
- model and monitor the impact of interventions, through digital twins;
- ensure uses of technology are 'energy proportionate', or in other words that they use computing power effectively. This should be part of a 'net zero assessment' of any technology-based approach;
- support improvements to the energy efficiency of devices;
- minimise the turnover of digital infrastructure and its embodied emissions; and
- enable operation under fully renewable energy.

Greater data availability and a continued analysis of underlying drivers of change will be necessary to produce reliable projections in future, and to drive decarbonisation.

Recommendations

Keeping track of the tech sector's own carbon footprint will require greater data availability. The sector's footprint can be reduced through multiple approaches, including the further uptake of renewables and the scrutiny of digital technologies' energy proportionality – ie whether specific data and computing applications bring benefits that outweigh their own emissions.

RECOMMENDATION 4

The tech sector should lead by example and make data accessible to allow the greater monitoring of its energy consumption and carbon emissions.

Government leaders should identify the levers to ensure tech companies share publicly data about the energy consumptions of their digital systems and products, including embodied and use phase emissions, in particular from data centres – this should include Scope 1, 2 and 3 emissions. This should be part of the National Data Strategy and could build on Defra's Greening Government: ICT and Digital Services Strategy. This would involve the Department for Digital, Culture, Media and Sport (DCMS), the Department for Business, Energy and Industrial Strategy (BEIS) and HM Treasury working together to identify and establish those levers.

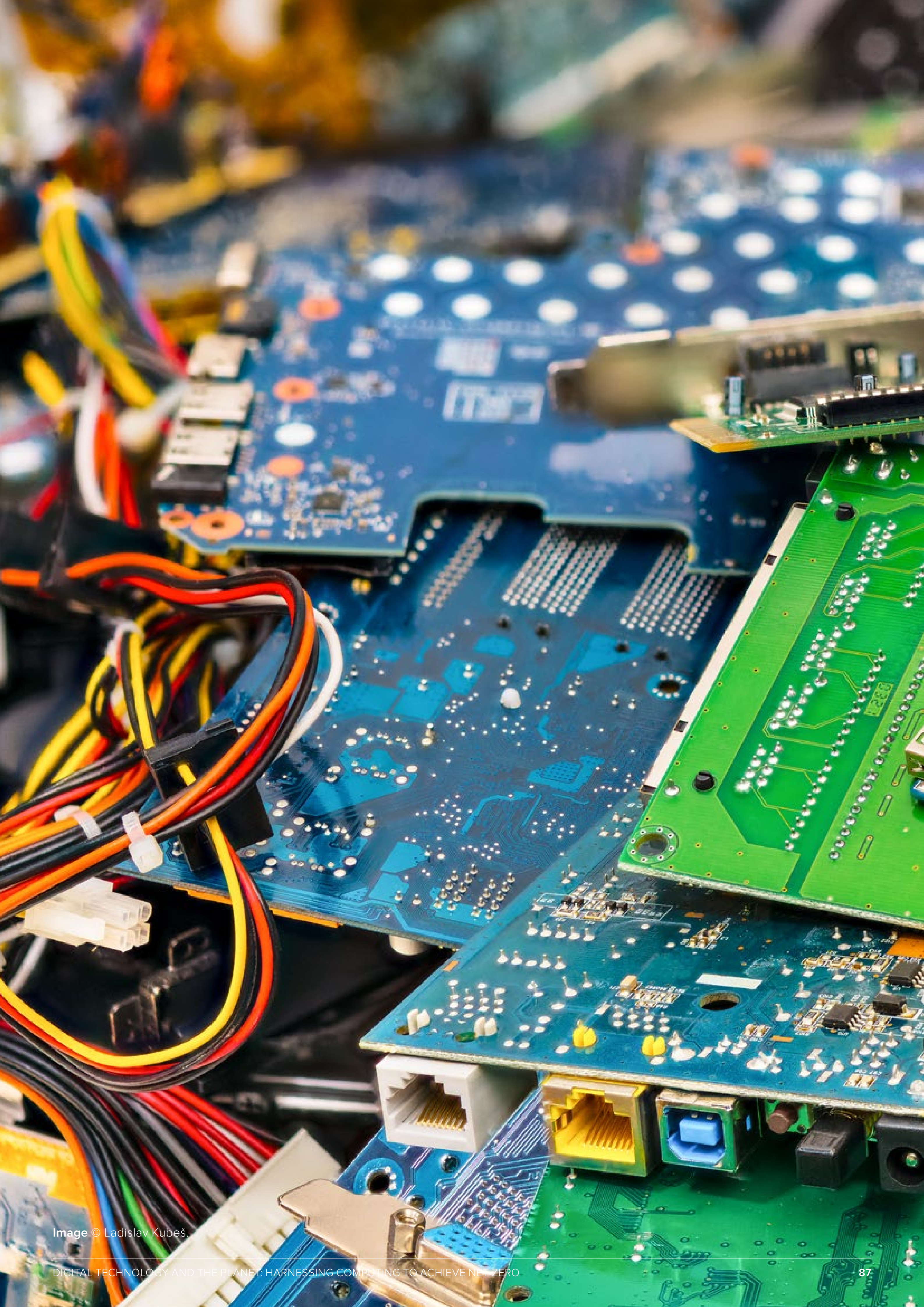
RECOMMENDATION 5

Tech companies should further promote the use of renewable energy for computing activities, for example by scheduling these activities, where appropriate, for times that maximise the use of intermittent renewable energy sources.

RECOMMENDATION 6

Regulators should develop guidance about the energy proportionality of digital applications.

Such guidance could set out key questions to consider when developing or deploying digital technologies. Where there are options to use less energy-intensive approaches, guidance should make this clear. For example, the Financial Conduct Authority should provide guidance on the energy intensity of blockchain-based applications used in financial systems.



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Chapter five
Establishing a data-enabled net zero economy and society

Left
© Chaay_Tee.

Establishing a data-enabled net zero economy and society

Recent years have seen the advent of 'as a service' business models, where companies sell a service rather than simply equipment or a commodity.

The digital revolution offers opportunities to accelerate the transition to a net zero economy, enabling society to reap the rewards of both innovative data uses and low-carbon ways of living and working. Achieving this transition requires business models and technology approaches that can create economic value from the use of data, supported by action at different levels to ensure everyone in society can access these and participate in new forms of economic activity. Rapid global change is required, which calls for interventions to develop and deploy digital technologies in pursuit of net zero.

Supporting new business models and a data-enabled shift in value creation

Some transitions to net zero will happen more readily than others. For example, data centres are likely to pursue efforts to be energy efficient as it makes economic sense for them to invest resources at hand to improve their environmental impact and save money. Whereas a shift in agricultural practice to reduce emissions might require interventions to provide farmers with training and funding, as well as incentives to change individual consumer food habits. Certain transformations, as in energy supply, will require doing away with legacy architectures and systems, and hence considerable investment and effort[236]. In some cases, brand new business models will need to be explored. Achieving widespread economic transformation will require a range of different incentives, reflecting the needs of sectors, locations, existing infrastructures and resources.

The sharing and circular economy

In some areas, new forms of business activity are already emerging, which are lower carbon and more resource efficient. For example, a number of digital platforms are already supporting the sharing and circular economies, such as online marketplaces specialising in the sale of second-hand items, or apps that let people borrow tools from their neighbours[237]. These new forms of business allow value creation without the need to manufacture new products.

'As a service' models

Business model innovations come with different challenges and will require support. Recent years have seen the advent of 'as a service' business models, where companies sell a service rather than simply equipment or a commodity. For example, 'mobility as a service' refers to a shift away from personally-owned modes of transport towards mobility provided as a service: in many cities there are, for instance, apps enabling people to locate and rent a bike for a short period. 'Mobility as a service' therefore potentially allows service provision, value creation and emission reductions due to increased use of public transport. However, there is an initial cost towards the creation of a shared infrastructure, which requires support from public or private investors.

236. *Op. Cit.* 60

237. Jaisoor NS 2018 The Sharing Economy is Good for the Environment. Here's Why. (see https://medium.com/nomobo/the-sharing-economy-is-good-for-the-environment-heres-why-db37214215f7, accessed 16 October 2020)

Similarly, 'heating as a service' would see consumers pay for the provision of a warm, comfortable home. While the current model of energy as a commodity means householders pay suppliers for the energy they consume, with heating as a service suppliers' revenues would increase if energy consumption went down. Energy suppliers would be incentivised to support home-owners in performing home energy-efficiency upgrades, including better insulation and the installation of smart home technologies and energy management systems.

Distributed energy sales

In the same sector, 'distributed energy sales' within a district would enable individual houses to buy and sell energy to each other, for example using smart contracts and negotiated tariffs. New intermediate companies have started to enter the market to mediate this energy trading. Distributed energy sales would potentially encourage the uptake of renewable energy generation and storage, and contribute to the decarbonisation of the grid. Drawing on the example of successful local district heating not-for-profit companies, such as Aberdeen Heat and Power, distributed energy sales could also contribute to the creation of local jobs[238]. However, several challenges exist in implementing distributed energy sales. One challenge here is technical, integrating district energy generation with local network supply, and will require further research.

A switch to different types of business models, such as 'heating as a service', could be supported by digital platforms and other frameworks. Such frameworks for managing information generated and used by technology for the planet will need coordinated implementation at industry-level, otherwise individuals will end up with multiple systems to manage and potentially conflicting software – eg solar panels that will not connect with a smart home system.

A major challenge for both 'distributed energy sales' and 'energy as a service' lies in making the cost of change worth the investment, and in balancing the costs between energy suppliers and households. Not all UK households may be able to afford home energy improvements, despite Government's Green Home Grants scheme[239]. For energy suppliers to be ready to bear the initial cost of the necessary equipment and home upgrades, they would likely want reassurance that users would stay long enough with them to make their investment worthwhile. This is very different from the current situation in the UK, where consumers switch energy suppliers every few years or so, in order to get better tariffs.

A market is starting to develop, however, for corporate clients to take up new energy business models. Centrica Business Solutions offers an Energy as a Service bundle, including the design, installation and financing of on-site power generation[240]. The supplier recovers the cost of the technology thanks to the energy savings realised through the length of the contract.

238. See https://www.aberdeenheatandpower.co.uk/about/ (accessed 16 October 2020)

239. Wired 2020 The Green Homes Grant is a bad deal for you and for the climate (see https://www.wired.co.uk/article/green-homes-grant, accessed 16 October 2020)

240. Lempriere M 2020 Centrica launches new Energy as a Service bundle to help businesses build back better (see https://www.current-news.co.uk/news/centrica-launches-new-energy-as-a-service-bundle-to-help-businesses-build-back-better, accessed 16 October 2020)

Some financial institutions are developing systems that use farming data to give parcels of land identifiable environmental scores, similar to credit scores.

New finance models

In land use, digital technology could support new finance models and the systematic use of new 'green' metrics. Some financial institutions are developing systems that use farming data to give parcels of land identifiable environmental scores, similar to credit scores, taking into account data about production, biodiversity and other indicators of land health. In future, such systems could be used more widely by landowners to invite subsidies or investment from governments or financial institutions, to adapt or best use land in line with the net zero target and SDGs. However, here again investment would be needed to create and maintain the supporting technical infrastructure, from sensors to data infrastructure.

Skills for the net zero economy and society

Jobs of the future will increasingly require data literacy and digital skills, and applying these to achieve net zero will require an understanding of climate change. Everyone needs basic data literacy skills in order to know how to use the smart meter in their home to the extent that they are able to learn and adopt patterns of lower emissions energy use. Individuals and organisations may deal differently with the disruption, and this will need to be managed to ensure a just transition to a data-enabled net zero economy.

A disruption for the workforce

The shift to a data-enabled net zero economy will mean faster rates of digitalisation across sectors. As digital technologies become more pervasive in the workplace, the skills that individuals require to operate alongside these technologies may change[241].

For example, operating the farm of the future will require farmers to have a very different set of skills from those they have today – they will need to be confident using digital interfaces to support their decision-making, and controlling the operation of autonomous systems. Digital technologies will have a disruptive effect on work, with some jobs being lost, others being created, and others changing.

It is difficult to make precise predictions as to exactly which jobs will see a fall in demand and the scale of new job creation. There are many different perspectives on 'automatability'. For example, there is a broad consensus that current AI technologies are best suited to 'routine' tasks, while humans are more likely to remain dominant in unpredictable environments, or in spheres that require significant social intelligence. With improvements in safety critical AI, driverless vehicles would more robustly deal with unpredictable situations, with implications for the workforce of the logistics sector.

Demand for new skills for the data-enabled net zero economy is increasing. For example, in manufacturing, and increasingly in other sectors, digital twin engineers may be recruited to set up and oversee the simulation of factories and other assets[242]. To take full advantage of digital twins, organisations will also need data scientists to analyse patterns and trends from real-time data collected by the industrial IoT and fed back by the simulated factory. The need for net zero aware software engineers is also a new need. In future, building capacity for greater emissions reporting will also require individuals with a new skill set.

241. The Royal Society and British Academy 2018 Evidence synthesis: The impact of artificial intelligence on work (see https://royalsociety.org/-/media/policy/projects/ai-and-work/evidence-synthesis-the-impact-of-AI-on-work.PDF, accessed 16 October 2020)

242. Deloitte 2018 The future of work in manufacturing: What will jobs look like in the digital era (see https://www2.deloitte.com/content/dam/insights/us/articles/4747_Manufacturing-personas/4747_Digital-twin-engineer-Interactive.pdf, accessed 16 October 2020)

Building capacity

The response to the current economic crisis triggered by the COVID-19 pandemic should focus on education and training in order to support a workforce and society with the resilience to navigate the coming decade.

To ensure everyone can take part in the data-enabled net zero economy, there is a need to build knowledge and digital skills for all, throughout the life course, and to widen access to data science and computer science education[243,244]. Everyone will also need a sound understanding of net zero. Given the number of years it takes to train and build experience, it is important that focus is given to this now. It will be essential to build a digital baseline as well as explore the cutting edge of digital capacity. To promote basic literacy on digital technology for net zero at school level, free resources could be developed to support teachers and parents who are home schooling to deliver the current curriculum. A good example of such free resource is Isaac Physics and Isaac Computer Science, used by 75% schools in England[245].

From the perspective organisations, many of the sectors concerned with the data-enabled net zero transformation do not currently have the appropriate corporate knowledge and digital skills base. To implement the digitalisation of energy systems, the sector will require individuals and teams with both knowledge of energy systems and digital skills. At board level, companies could appoint a net zero officer. There may be a role for nimble training programmes and opportunities for upskilling workers. The applied nature of data science also fits with apprenticeship mechanisms[246].

Organisations will also need to recruit highly skilled data scientists, which can prove challenging as they are in high demand. There are multiple drivers for the movement of data science professionals across academia and the private and public sectors – from salary to access to data and computing power, and these drivers can be leveraged to attract talent[247].

There are a number of existing initiatives that help share best practice in embedding sustainability in business. For example, digital innovation is becoming an integral part of sustainable construction, and the Supply Chain Sustainability School acts as a hub for knowledge across the industry. It supports the digitalisation of business towards sustainability, by sharing information on processes around Building Information Modelling and data management, alongside other resources[248]. Trade associations, such as the Chartered Institution of Building Services Engineers provide a benchmarking tool with access to data about buildings energy use, as well as other resources[249]. More skills programmes, or platforms to share best practice in technology use and data management, could help spread ideas around the use of data and digital technology for net zero.

There are also mechanisms to share talent that sectors seeking to digitalise towards net zero could tap into. Shared industry-academia positions and braided careers could be further supported. In addition, there is value in encouraging sustainability mentorship and in enabling data scientists to donate their time to applying data science to societal challenges such as climate change.

Given the number of years it takes to train and build experience, it is important that focus is given to this now.

243. *Op. Cit.* 12
244. *Op. Cit.* 13
245. See https://isaacphysics.org/ and https://isaaccomputerscience.org/, accessed 16 October 2020)
246. *Op. Cit.* 13
247. *Op. Cit.* 13
248. See https://www.supplychainschool.co.uk/topics/bim/process-technology/ (accessed 16 October 2020)
249. *Op. Cit.* 104

Broadband speeds in rural areas lag behind those in urban areas, and only 12% of UK homes and offices have access to full-fibre broadband.

Ensuring policies address digital divides and inequalities

Change will affect different groups in different ways. Evidence from historical and contemporary studies indicates that technology-enabled changes to work tend to impact on lower-paid and lower-qualified workers more than others[250]. This suggests there are likely to be significant transitional effects which cause disruption for some people or places. One of the greatest challenges raised by digitalisation is therefore a potential widening of inequality, at least in the short term, if lower-income workers are disproportionately affected and benefits are not widely distributed.

Interventions should address the digital divide and create job opportunities across the country. A failure to achieve a just transition could lead to backlashes that risk jeopardising chances to reach net zero by 2050. Conversely, reducing inequality in access to digital technology and increasing digital and net zero literacy across the UK will help accelerate the transition to net zero.

Certain interventions and changes will impact various communities differently, which raises the question of who bears the cost of such externalities. For example, the potential of these technologies to enable new ways of working were thrown into the spotlight as societies sought to adapt to the COVID-19 pandemic, with increasing use of videoconferencing and home working. However, this period has also shown the limitations of these systems, and the consequences of unequal access, with some groups excluded from the benefits they offer. Broadband speeds in rural areas lag behind those in urban areas, and only 12% of UK homes and offices have access to full-fibre broadband[251]. Those who develop incentives for the deployment of technologies need to be mindful of this and consider fundamental questions about how vulnerable groups might be affected by the roll out of digital technologies for net zero. Participation, as discussed in chapter 3, will be key.

Investment in the digital infrastructure for net zero

There is mounting evidence about the effectiveness of investment in green infrastructure in stimulating the economy and generating jobs[252 – 255]. Clean energy contributes to £13bn in annual investment in the UK. The Department for Business, Energy & Industrial Strategy (BEIS) estimates that in 2017 there were around 400,000 jobs in low carbon businesses and their supply chains in the UK, which could grow to 2 million by 2030[256].

250. *Op. Cit.* 241
251. See https://www.ofcom.org.uk/about-ofcom/latest/media/media-releases/2020/broadband-networks-during-pandemic (accessed 16 October 2020)
252. *Op. Cit.* 17
253. KPMG 2020 Green fiscal stimulus: Why it is needed and how to implement it (see https://assets.kpmg/content/dam/kpmg/uk/pdf/2020/06/green-fiscal-stimulus.pdf, accessed 16 October 2020)
254. World Economic Forum 2020 Now is the time for a 'great reset' (see https://www.weforum.org/agenda/2020/06/now-is-the-time-for-a-great-reset/, accessed 16 October 2020)
255. McKinsey 2020 How a post-pandemic stimulus can both create jobs and help the climate (see https://www.mckinsey.com/business-functions/sustainability/our-insights/how-a-post-pandemic-stimulus-can-both-create-jobs-and-help-the-climate#, accessed 16 October 2020)
256. HM Government 2019 Leading on Clean Growth – The Government Response to the Committee on Climate Change's 2019 Progress Report to Parliament – Reducing UK emissions (see https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/839555/CCS0819884374-001_Government_Response_to_the_CCC_Progress_Report_2019_Web_Accessible.pdf, accessed 16 October 2020)

An analysis by McKinsey estimated that, for an average European country with a population of 50 – 70 million, a retrofit of houses for energy efficiency could cost 50 – 80 billion euros and create 0.8 to 1.7 million jobs; the installation of smart building systems would only cost 0.1 – 2 million euros and create an additional 2 – 40 thousand jobs – adding to the case that investment in both would help a step change in emission reductions[257]. Further data analysis will have a role in monitoring the impact of interventions towards a green recovery from the COVID-19 pandemic, helping learn lessons and target future interventions on the path to net zero[258]. The Green Alliance Tech Task Force recently highlighted that the UK's environmental policy does not prioritise environmental goals, while environmental policy is not making the most of digital solutions, recommending that this should change and that Government invest in smart, net zero compatible infrastructure as well as strengthen skills and capabilities[259].

Participants at Royal Society workshops proposed a number of projects, which, if started today, could begin to contribute to net zero within the next year or so. Box 14 presents a selection of these.

Levers to accelerate widespread action

In addition to national and local support for low-carbon services and the upskilling of the workforce, a number of additional levers will be instrumental in steering the recovery from the COVID-19 and achieving net zero. Incentives could in particular seek to harness societal and behavioural levers, financial levers, and international levers, in order to catalyse change across society, the economy and countries around the world.

Societal and behavioural levers

Individuals and civil society play a key part in pressing for change towards net zero. This, together with a greater digitally-enabled monitoring and availability of information, presents an opportunity to accelerate change.

Consumer opinions, choices and behaviours will play an important part in the shift towards a net zero economy. For example, raising consumers' awareness of the impact of the energy performance of their current or future homes – based on better data – will support low carbon choices and drive market-wide changes. Lifelong learning programmes and campaigns would inform and encourage greener individual choices. Data science and simulations can help monitor the impact of infrastructure and interventions on individual behaviours and help design an effective framework to support societal transformation.

As consumers' awareness of the environmental impact of goods and services increase, green investment by large organisations enables them to build trust with consumers, a form of 'trust for green'. Businesses around the world are already building such a 'trust for green' by adopting sustainable practice and obtaining certifications such as 'B corporations'. Investing in applications of digital technologies for net zero and communicating about it might similarly reflect positively on brands.

For an average European country with a population of 50 – 70 million, a retrofit of houses for energy efficiency could create 0.8 to 1.7 million jobs.

257. *Op. Cit.* 255

258. edie 2020 Analysts to help align economic recovery plans with net-zero (see https://www.edie.net/news/9/Analysts-to-help-businesses--investors-and-policymakers-align-economic-recovery-plans-with-net-zero/, accessed 16 October 2020)

259. Green Alliance 2020 Smart and green: joining up digital and environmental priorities to drive the UK's economic recovery (see https://www.green-alliance.org.uk/smart_and_green.php, accessed 27 October 2020)

BOX 14

Projects that could be initiated now and achieve rapid impact towards net zero.

Participants at Royal Society workshops proposed a number of projects, which, if started today, could contribute to net zero within the next year or so, eg:

Buildings

- Combine interventions to expand broadband access focusing on areas of poor connectivity and to retrofit homes with insulation and smart controls.
- Require a minimum Energy Performance Certificate rating whenever a house or flat is sold, leased or rented. Since residential properties change ownership every 15 years on average, this could have a significant impact on the retrofitting of the existing housing stock by 2050.
- Create a useable digital twin of the whole UK building stock. This digital twin would help local and national government plan its net zero transition, help occupants decide what improvements are most valuable for their property and check the impact of such interventions. A pilot version is already helping the Greater London Authority[260].

Energy supply

- Prototype a digital infrastructure to enable an evolved and decarbonised, decentralised energy supply in the UK. Different ownership, regulatory and market models would need to be considered. Prototypes could enable demonstration and de-risking of national scale solutions.
- Investigate how AI could enable optimal grid integration and green hydrogen generation at distributed points of use. The project would develop solutions to optimise the production of renewable power while balancing the grid.

Supply chains

- Encourage companies to share supply chain data to build an accurate global map of goods transportation. This would assist in planning the reduction of associated emissions.
- Apply AI methods to data from satellite imagery, weather forecasts and ocean sensors to map out the most carbon-efficient routes and timings for sailing large ships. An increase in efficiency of a few percents would make a sizeable difference in terms of emissions.

Other

- Invest in a national Living Lab so digital businesses can test and learn how to deliver innovative new low carbon solutions that work for a broad range of consumers.
- Fund every local area to develop a detailed energy strategy setting out how they will reach net zero.
- Mandate that all meetings that come under UKRI funded research offer the option to join remotely.

260. *Op. Cit.* 55

Conversely, as exemplified in the energy sector, if companies fail to use data for greener and smarter energy systems, they risk losing the trust of consumers[261].

Civil society and activists have also raised the profile of climate issues in recent years[262]. Building on the greater level of emissions monitoring and transparency enabled by digital technologies, civil society movements can use this evidence to inform decisions and trade-offs individuals and society must make, and increase pressure on government and corporates to accelerate the transition to net zero.

Green finance

Private investment also has a considerable role in accelerating the development and uptake of data-driven systems supporting net zero. Investors are increasingly using businesses' track record in Environmental and Social Governance (ESG) and climate-related risk disclosures as a means to shape their portfolio. They might favour investment in those companies for multiple reasons. Emerging evidence shows that companies that score well in terms of (ESG) also did better during COVID-19 lockdowns, suggesting a link with greater resilience[263].

This report outlines the scale of the opportunity in investing in the development of data-driven systems for net zero. Such systems also generate valuable data, meaning that, as a result of their investments, financial firms could also benefit from better intelligence.

Currently, the Financial Stability Board's Taskforce on Climate-related Financial Disclosures recommends that business disclose Scope 1, Scope 2 and if appropriate Scope 3 greenhouse gas emissions on an annual basis. There are ongoing efforts in the UK to make such disclosures a requirement[264]. Further reporting and availability of data could not only inform the analysis of climate trends and the impact of policy interventions on emissions (see chapter 2), but also green investment. Further to this, the systematic reporting of Scope 3 emissions would help drive change through supply chains.

International levers

Limiting the increase in global average temperature to well below 2°C and pursuing efforts towards 1.5°C will require action across the globe. International collaborations can help move the issue on several fronts. For example, the Montreal Statement on Sustainability in the Digital Age calls for a global collaboration among business, civil society, researchers, and innovators to focus on leveraging AI and the digital age to help build a sustainable and equitable world[265]. The World Economic Forum has called for a 'great reset' for the world economy to achieve a green and equitable recovery from the COVID-19 crisis, with digital identified as an essential component[266]. It also called for the development of common metrics for sustainable value creation, grounded in the SDGs[267].

Emerging evidence shows that companies that score well in terms of ESG also did better during COVID-19 lockdowns, suggesting a link with greater resilience.

261. *Op. Cit.* 141
262. BBC 2019 General election 2019: How big an issue is climate change for voters? (see https://www.bbc.co.uk/news/science-environment-50307304, accessed 16 October 2020)
263. HSBC 2020 ESG stocks did best in COVID-19 slump: Climate and sustainable investments outperformed as pandemic struck (see https://www.gbm.hsbc.com/insights/global-research/esg-stocks-did-best-in-corona-slump?_, accessed 16 October 2020)
264. Financial Times 2020 UK-listed companies face compulsory climate disclosures (see https://www.ft.com/content/de915fb4-5f9e-11ea-b0ab-339c2307bcd4, accessed 16 October 2020)
265. CIFAR, UKRI, CNRS, Future Earth, The Observatory of Social Impacts on AI and Digital Technology, UK Office for AI 2020 The Montreal statement on sustainability in the digital age (see https://sustainabilitydigitalage.org/montreal-statement/, accessed 16 October 2020)
266. *Op. Cit.* 254
267. World Economic Forum 2020 Toward Common Metrics and Consistent Reporting of Sustainable Value Creation (see https://www.weforum.org/whitepapers/toward-common-metrics-and-consistent-reporting-of-sustainable-value-creation, accessed 16 October 2020)

BOX 15

An opportunity for a rapid transition in mid- and low-income countries

The shift to a digitally-enabled net zero economy will involve different paths in different parts of the world. For example, mid- and low-income countries might have an advantage in leveraging best practice when developing their digital infrastructure from scratch, as opposed to having to depart from legacy systems. This creates an opportunity for developing and emerging economies to leapfrog the global North[268]. Investment in these countries could therefore be particularly high impact.

These countries can also take advantage of existing global technology platforms, to enable implementation speed, save cost, achieve efficiency and change lives. Free services they can build on include search engines, messaging platforms, or GPS. The Google project Sunroof provides free solar energy mapping, helping guide the installation of solar panels – urban centres in sub Saharan Africa were not in the initial areas covered by the project, but such mapping would present great opportunities for development. Collaborations between the tech sector and locally-based Non Governmental Organisations, or 'tech for good' small companies, can drive solutions benefiting the environment and empowering local populations – for example, using infrastructure from Microsoft, SunCulture developed IoT and AI-based farming solutions in Africa[269].

Mid- and low-income countries might also take advantage of fewer barriers to the deployment of new technology. For example, Rwanda has trialled drug delivery by drones, which could be really beneficial in completing the final leg of a distribution chain and reaching remote locations[270]. In the UK this would be complicated by rules that mean drones can only be flown in line of sight. But countries with much less crowded airspaces do not have this issue and can therefore benefit from such developments. Similarly, there are projects using drones to plant tree seeds and restore mangroves, for example in Myanmar[271].

268. Hopper A 2017 Bakerian Lecture (see https://royalsociety.org/science-events-and-lectures/2017/03/bakerian-lecture/ accessed 16 October 2020)

269. See https://www.microsoft.com/en-ca/ai/ai-for-earth-SunCulture (accessed 16 October 2020)

270. *Op. Cit.* 268

271. World Resource Institute and The Nature Conservancy 2017 The business of planting trees: A growing investment opportunity (see https://www.nature.org/content/dam/tnc/nature/en/documents/Business_of_Planting_Trees_Report.pdf, accessed 16 October 2020)

The Global Partnership for Sustainable Development Data (see Box 9) is supporting multi-stakeholder efforts to promote the use of data with benefits to the environment and to people. In Tanzania, data is already used to some extent towards a number of Sustainable Development Goals, from understanding weather patterns to improve food security, to studying water availability or cook stove usage data – opening up more datasets could spur further local innovation[272]. In Ghana, the UN Development Programme (UNDP) sponsored a multi-stakeholder Waste Recovery Initiative to promote a circular economy, which involves developing a digital platform with a number of tools (eg waste resource map, compendium of technologies etc.) to provides real time data on waste management and facilitate material exchange[273]. Tanzania's National Bureau of Statistics produced a recent report on e-waste[274], and developed a state of climate change statistics report which captures greenhouse gas emissions and approaches to reducing them[275]. This offers a good example for the development of environmental statistics units across sub-Saharan Africa.

The COP26 UN Climate Change Conference and the COP15 UN Biodiversity Conference could be momentous international events in progressing the global climate and sustainability agenda. If countries sign up to carbon budgets that meet the 1.5°C target, and if they set the right policy and innovation environment, digital technologies can be used as an enabler across all sectors. The shift to a digitally-enabled net zero economy will involve different paths in different parts of the world (see Box 15). With COP26 and other international fora, the UK has an opportunity to lead, for example with an initiative on a robust data-driven approach towards achieving a reliable carbon credits market internationally, with a focus on supporting developing economies.

Crucially, prevailing policy conditions are likely to have a wider impact on the development and use of digital technologies than the more targeted, sector-specific policy interventions. Such policies might include carbon pricing, incentives for the circular economy, support for the development of renewable energy sources, and for smart grids.

272. Global Partnership for Sustainable Development Data 2018 Climate Change Open Data for Sustainable Development: Case Studies From Tanzania and Sierra Leone (see https://www.data4sdgs.org/sites/default/files/services_files/WRI%20Climate%20Data_FINAL2_optimized.pdf, accessed 16 October 2020)

273. See https://www.gh.undp.org/content/ghana/en/home/projects/waste_initiative.html (accessed 16 October 2020)

274. Tanzania National Bureau of Statistics 2019 National E-Waste Statistics Report (see https://www.nbs.go.tz/index.php/en/census-surveys/environmental-statistics/483-national-e-waste-statistics-report-2019-tanzania-mainland, accessed 16 October 2020)

275. In press at time of publication of this report.

Recommendations

Rebuilding the economy after the COVID-19 pandemic should focus on building a low-carbon economy, utilising data and digital technologies to achieve this. A focus on skills is essential to enable everyone to take part and accelerate a data-enabled net zero transition. COP26 presents an opportunity for the UK to demonstrate leadership in the digitalisation of the net zero transition and secure global change.

RECOMMENDATION 7

Action is needed to build digital and net zero skills at all levels – from basic literacy to advanced data analysis skills, and from an appreciation of efficiency to an in-depth understanding of carbon externalities. Re-tooling the workforce in this way will require a coordinated approach to nurturing data science and net zero skills across the country.

- The National Data Strategy, developed by DCMS, should prioritise action to equip the UK with the skills to drive a data-enabled net zero revolution, and DCMS could prioritise the use of data for net zero within the National Data Strategy missions.
- BEIS' and the Ministry for Housing, Communities and Local Government's (MHCLG) joint Cities and Local Growth policy team should prioritise skills for a data-enabled net zero economy at the local level, providing annual reports on progress in increasing digital skills in local communities. Local Enterprise Partnerships should push digital skills in the local economy, for example by auditing whether universities and local employers are collaborating to identify and meet local digital skills and net zero skills needs.
- To support the development of a data-enabled net zero economy across the country, research institutes, the Energy Systems Catapult and Digital Catapult, learned societies and charities should provide information resources and toolkits to support local energy and environmental initiatives led by volunteers or social enterprises. There is also a role for training providers to develop agile and nimble opportunities for individuals to reskill and upskill as the nature of their job changes due to digitisation.

RECOMMENDATION 8

The UK Government should use COP26 as an opportunity to lead the way in establishing ambitious programmes that bring together governments, industry and the third sector – committing funding, data, skills, and computing facilities – to develop computing as infrastructure for the planet.

The UK Government could put forward an initiative on a robust data-driven approach towards achieving a reliable carbon credits market internationally, with a focus on supporting developing economies.

Image © Halfpoint.

Chapter six
Digital technology for the planet: a research and innovation mission

Left

Digital technology for the planet: a research and innovation mission

Developing a research and innovation mission, centred in a set of research challenges, in conjunction with ensuring adequate investment, policies and multi-stakeholder engagement strategies, will be essential to enable this collective effort.

Creating the next generation of digital technology applications to meet the net zero target will require a substantial research and innovation effort. A collective effort, from academia, industry, the public sector and civil society is needed to help catalyse rapid progress in the most promising research directions or applications for net zero. Developing a research and innovation mission, centred in a set of research challenges, in conjunction with ensuring adequate investment, policies and multi-stakeholder engagement strategies, will be essential to enable this collective effort.

A set of research and innovation challenges

The evidence presented in this report points to a set of emerging research and innovation challenges that should be prioritised to realise the full potential of the digitalisation of the net zero transition:

- Transforming energy and digital systems to allow greater integration and optimisation;
- Creating a data infrastructure for net zero;
- Developing safe and robust core digital capabilities towards a 'control loop' for the planet;
- Developing new green computing approaches;
- Developing digital technology to enable other mitigation activities;
- Distributing fairly the costs and benefits of the data-led net zero transition.

Transforming energy and digital systems to allow greater integration and optimisation

The digitalisation of energy systems is essential for their decarbonisation, with digital technologies playing a key role in enabling the integration of multiple, distributed and intermittent energy sources. In turn, there is a complementary ambition from the computing sector to run entirely on intermittent renewable sources of energy and to be scheduled in ways that contribute to the energy grid demand management process.

An important research challenge here will be in the development and deployment at scale of intelligent computing systems that can integrate data from energy systems and data centres in order to guide the planning and operation of these systems. These could help create a 'control loop' between the energy and digital systems, enabling the intelligent scheduling of computing jobs at times of peak production from renewables. Tackling this research challenge will require the development of core capabilities in AI and digital twinning, and applications tailored to the energy system. It could also build on research exploring parallels between electricity grids and the internet[276]. There is a unique opportunity for the tech and energy sector to pool together their best resources to tackle this challenge.

276. Keshav S and Rosenberg C 2010 How internet concepts and technologies can help smarten the electrical grid. Green Networking. (see http://svr-sk818-web.cl.cam.ac.uk/keshav/papers/10/greennet.pdf, accessed 16 October 2020)

Creating a data infrastructure for net zero

Data about energy use and emissions, from across sectors and supply chains, can be used to support the development of digital information technologies for monitoring emissions and enforcing climate targets. Broader datasets from across the same sectors, about their assets, processes and performance, will lead to the development of new applications of digital technologies for net zero. Such data needs to be made available whilst managing a number of dilemmas.

This challenge would investigate how to create new forms of value from data access, how to ensure data meets the necessary requirements – for findability, accessibility, interoperability and reusability – and what the trusted third parties, legal frameworks and infrastructure for handling that should be.

This challenge would also involve building prototypes of data infrastructure that support digital twinning, including modelling and feeding back information to physical systems. Such prototypes would demonstrate value in optimising and reducing emissions. Early research should also quantify the impact of digital technologies and various interventions on emissions.

Developing safe and robust core digital capabilities towards a 'control loop' for the planet

The safe and rapid deployment at scale of data-driven systems for net zero will require that the core digital capabilities described in Chapter 1 (see Figure 3 and Box 3) are developed so they embed the following characteristics of trustworthy technology outlined in Chapter 3 (see Summary Table below).

SUMMARY TABLE

Core digital capabilities	Characteristics of trustworthy technology
• Model, optimise and predict • Integrate, analyse and map data • Simulate (digital twinning) • Sense, connect and actuate • Track and verify	• **Contestation** – Transparency about data provenance – Explainability – Auditability • **Participation** – Usefulness, usability and comprehensibility for users – Participatory design • **Resilience** – Reliable service availability – Ability to operate at different scales – Cybersecurity – Longevity and interoperability – Flexibility and redundancy – Verification and robustness, including safety critical AI

Decision support systems for net zero might include tools to track the provenance of goods or their emissions, and the development of interfaces that allow human users to interrogate the workings of digital systems. Developing more effective digital decision-support systems for net zero will require user-friendly interfaces that present meaningful, actionable information. It will require an ability for users to interrogate how intelligent systems arrived at a given conclusion and the origin of the data this conclusion is based on. These data-driven information interfaces will also need to integrate a wide range of data, some of which might be sensitive, and they might need to incorporate Privacy Enhancing Technologies in their design. Further research is needed to develop these trustworthy information interfaces.

The critical digital infrastructure for net zero will need to be robust and resilient. In order to create data-driven systems for net zero with greater resilience, further consideration is needed to address the risks that digital systems are subject to (eg cybersecurity; issues in scalability) and to draw on best practice in building resilient cyber-physical systems (eg redundancy; interoperability).

Developing new green computing approaches

Chapter 4 set out some of the research areas into green computing that will allow keeping the energy demand and emissions of digital technology in check. It includes:

- Energy-efficient algorithms and software
- New forms of low power processors
- Advances in neuromorphic computing and AI accelerators
- Advances in low-carbon supercomputing
- Increasing longevity of computing infrastructure

This challenge also involves identifying further ways to reduce the energy consumption from digital infrastructures. Building on the research challenge of better integrating energy and digital systems, described above, there should also be a focus on enabling uptake of renewable energy in data centres.

Developing digital technology to enable other mitigation activities

Research and innovation will be key to deliver the harder to decarbonise areas, such as agriculture and aviation. As outlined in chapter 1, digital technologies offer ways to support technology-based greenhouse gas removal and nature-based solutions to climate change mitigation. These are pivotal in achieving the net zero target, and further research and development is needed to deliver the potential of carbon capture technologies for instance. Data science could help scientists discover materials and catalysts to enable carbon capture.

Distributing fairly the costs and benefits of the data-led net zero transition

A key challenge in the net zero transition is about distributing fairly its costs and benefits[277]. The digitalisation of the net zero transition brings its own specific challenges and opportunities. For example, the use of smart controls in buildings is more likely to lead to a reduction in energy consumption if suppliers provide them as part of an 'energy as a service' model (see chapter 5). These new data-enabled business models will require further research and development, including about the shape of existing markets and how new models could disrupt them, capital pathways, quantifiable global benefits, and fiscal incentives. It will also require investigating the drivers influencing societal transformation.

As an opportunity to distribute the benefits across society, the roll out of digital technology for the planet could involve new forms of social enterprises, which could be set up and help create jobs locally. Research should explore the forms these could take and pilot such social enterprises. Participation will be key to the success of the digitalisation of the net zero transition (see chapter 3), and this includes a role for participatory design and for social sciences research.

Creating the conditions for progress towards these research challenges

These research challenges are by nature ambitious and multi-disciplinary. To create digital applications adapted to a range of sectors, it will be necessary to develop stakeholder-led solutions to key challenges, highlight areas of opportunity and direct funding to them. Achieving this ambition will require collaboration between technology and domain experts, shared vocabularies and frameworks for effective research collaborations. It will also require investment measuring up with the scale of the ambition.

Research collaborations and open development

Action to achieve net zero will be required across sectors, communities and countries, which have different resources and strengths. There may be an opportunity to learn from and build on existing frameworks such as Mission Innovation, a global initiative for clean energy innovation[278]. There is a case for widening access to resources – data, computing power, skills – and taking a collaborative approach to innovation, drawing on respective strengths to tackle a common goal. For example, efforts to scale research collaborations between organisations (or groups of organisations) to achieve system-level change can benefit from decentralised approaches to technology development.

> Achieving this ambition will require collaboration between technology and domain experts, shared vocabularies and frameworks for effective research collaborations.

277. HM Treasury 2019 HM Treasury's review into funding the transition to a net zero greenhouse gas economy: terms of reference (see https://www.gov.uk/government/publications/net-zero-review-terms-of-reference/hm-treasurys-review-into-funding-the-transition-to-a-net-zero-greenhouse-gas-economy-terms-of-reference, accessed 16 October 2020)

278. See http://mission-innovation.net/about-mi/overview/ (accessed 16 October 2020)

> Open, permissively licensed repositories of foundational IP, together with the ecosystem to support and maintain them, would constitute a 'logical infrastructure' supporting technological innovation.

By ensuring technology and software is widely available, organisations can lower the barriers to creating and deploying new applications or developing further collaborations. Open development approaches are already common in fields such as machine learning, and widespread adoption of these norms could spur further action.

In addition to engaging diverse research communities, there may be meaningful ways of actively engaging the wider public in this endeavour. For example, citizen science[279] – research typically involving citizens in the collection or analysis of data – would give everyone an active role and empower citizens to contribute to building data-driven systems for the planet. Microsoft's 'planetary computer' involves citizens in monitoring biodiversity, through the capturing and sharing of photos of wildlife, which is then used to train machine learning algorithms[280]. Innovation competitions are another way to encourage wider participation.

New approaches to innovation

Investment in research and innovation will be critical, alongside new ways of enhancing the pipeline of research and innovation. In the UK, the Clean Growth Strategy and the Industrial Strategy Challenge Funds should be updated to reflect the net zero imperative. To attract funders, investment will need to show some consistency and stability.

The scale of the net zero challenge demands alternative models be explored: for example, an incubator for digital technology for net zero[281], a net zero ARPA challenge, or a community interest lab focused on challenges to do with digital technology for net zero (see Box 16). To speed up innovation, enable synergies and achieve greater impact, a condition for investment could be the release of the foundational IP created during the funded projects under a permissive open-source licence, and committing to maintain it. Open, permissively licensed repositories of foundational IP, together with the corporate, fiscal and legal ecosystem to support and maintain them, would constitute a 'logical infrastructure' supporting technological innovation – a set of high-quality building blocks for general use.

Regulators also have a part to play in lowering the regulatory barriers for innovative services and business models to come to market[282]. Ofgem announced an expansion of its regulatory sandbox service to support innovative services and business models contributing to the decarbonisation of energy[283]. Under this service, rules can be relaxed for innovative trials, such as rules around the connection, and use of, the electricity distribution networks.

There may also be a role for participatory research and social enterprises, and for finding effective ways of helping cities and place-based approaches. There might be a role for organisations that fill the gaps of local expertise. An example of that are the UN Global Pulse labs, which facilitate access to expertise to develop local applications of data and AI for SDGs[284].

279. The Royal Society 2012 Science as an Open Enterprise (see https://royalsociety.org/topics-policy/projects/science-public-enterprise/report/, accessed 16 October 2020)
280. See https://innovation.microsoft.com/en-us/planetary-computer (accessed 16 October 2020)
281. For example, this is one of the functions of the proposed International Centre for AI, Energy & Climate: https://www.icaiec.org/ (accessed 16 October 2020)
282. HM Government 2019 Regulation for the Fourth Industrial Revolution. (see https://www.gov.uk/government/publications/regulation-for-the-fourth-industrial-revolution, accessed 18 November 2020)
283. Ofgem 2020 Decarbonisation programme action plan (see https://www.ofgem.gov.uk/system/files/docs/2020/02/ofg1190_decarbonisation_action_plan_revised.pdf, accessed 16 October 2020)
284. See https://www.unglobalpulse.org/labs/ (accessed 16 October 2020)

BOX 16

Community interest laboratories to achieve net zero with digital technology.

Rapid progress in research and innovation is needed to address the major societal challenge of achieving net zero. A new and ambitious framework could boost the UK's ability to attract world-leading talent, deliver innovative solutions and bring them to market. The forward-looking framework for research, innovation, and wealth creation outlined below is an example new model that could be implemented to develop digital solutions to net zero. It takes inspiration in the UK's successful experience of Xerox PARC, Bell Labs, DEC labs, and Olivetti/ AT&T Cambridge.

Tackling climate change through digital technologies calls for a mould-breaking approach to research and innovation, with an ability to take considered risks. The proposed framework would be making bets on "unbelievable truth" outcomes (what nobody expects to happen) – steps ahead from what can be imagined with incremental progress. The framework would establish new laboratories, rather than consortia, with a vision-based sequence of projects and tangible deliverables.

A series of laboratories would be created across the country which would carry out research and build fully engineered prototypes and platforms, beyond what can be done in universities, or is likely to be done in industry ('too high risk'). These laboratories would produce scaleable and robust demonstrators, a showcase environment which creates case studies, narratives, and leadership opportunities for the UK. The centres would also research and develop new business models, incorporating shape of markets, capital pathways, quantifiable global benefits, and fiscal incentives.

The new laboratories would act as procurers for industry and universities, in an ARPA-lite style. They would also encourage talent to spin-out companies and teams. These attractive centres could lead to the establishment of high-tech industrial clusters and supply chains in UK. The diffusion of innovative solutions would be facilitated through minimal intellectual property (IP) barriers, such as permissive licences, open source, or standard contracts. There would be minimal price and simple rules for the release of IP, with 'use-it-or-it-recycles' contracts for recipients.

Such a framework could be uniquely attractive to top-talent from anywhere, in particular those with an interest in or an experience of working in between industry and academia. Publication would not be the leading indicator of success but used as appropriate. Following selection, world-class individuals would have the freedom to choose and execute projects, with the flexibility to explore new projects part of the time. They would also be encouraged to use money, industrial assets and teamwork to bring forward delivery. Hierarchies would be flexible to ensure early career researchers feel unencumbered. Additional support personnel could be employed and brought in as required.

In terms of governance, the framework would best be a not-for-profit entity with its own Board of Directors to give independence and resilience. It could for example be set up as a Community Interest Company, with a fixed life-time of twenty years. The scheme would be mostly government funded. There could be additional contributions from large technology companies in cash and through access to their computing platforms, software, and data. Charitable foundations might also make sector-specific financial contributions.

Research and innovation clusters can bring substantial value, prosperity and jobs to the surrounding region[285]. Since the evidence suggests that 'creating a cluster' is a misguided policy objective the government should focus on creating the conditions that allow clusters to emerge[286]. This includes taking measures to identify areas of absolute or comparative research strength, unlocking access to private and public funding, and developing supportive regulation and infrastructure.

Recommendations

A number of research and innovation challenges need addressing in order to realise the full potential of the digitalisation for the net zero. This calls for an urgent and ambitious collaborative research and innovation effort.

RECOMMENDATION 9

The UK Government's policies should be updated to reflect the net zero imperative.

For example the Clean Growth Strategy and Industrial Strategy Challenge Funds on artificial intelligence (AI) should explicitly seek to harness the digital revolution and directing research and development activities to achieve climate goals. To boost collaboration to tackle climate change, and to increase university-business connectivity in particular, Challenge Funds should comprise collaborative grants and large programmes of interconnected grants.

285. Catalyst, for example, formerly the Northern Ireland Science Park, has been critical in making Northern Ireland the second-fastest growing region of the UK. The Centre for Secure Information Technologies, which sits in this cluster, has formed the centre of a local cybersecurity ecosystem that includes over 40 companies employing approximately 1,600 cybersecurity professionals and delivering £60 million per annum in salaries to the local economy.

286. The Royal Society 2020 Research and innovation clusters (see https://royalsociety.org/-/media/policy/Publications/2020/2020-07-research-and-innovation-clusters-report.pdf, accessed 16 October 2020)

RECOMMENDATION 10

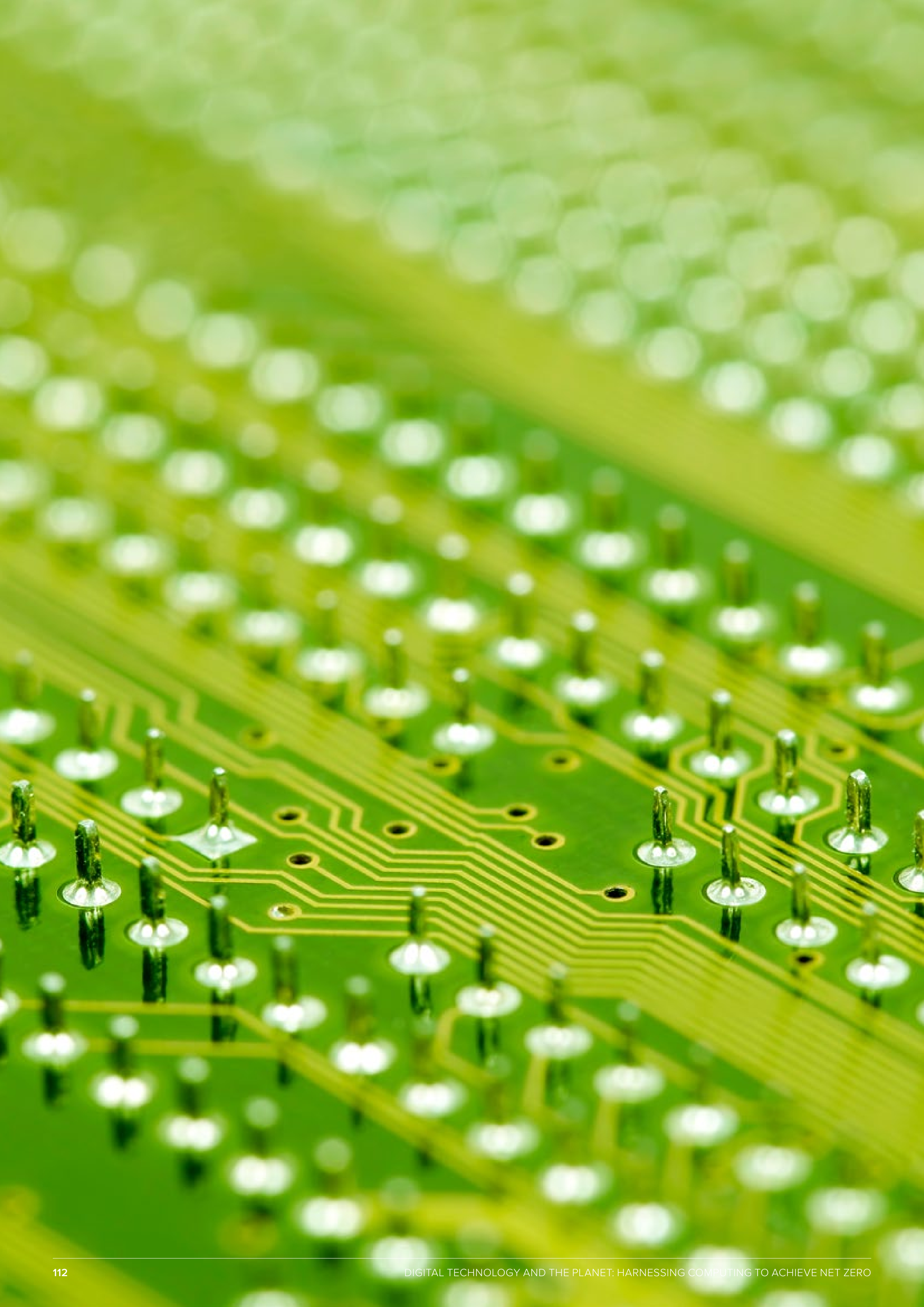
Regulators should provide frameworks to help business innovating in the space of digital applications for net zero, acknowledging the need for a step change in innovation to adapt to the net zero agenda and enable the green recovery.

This can be based on adaptive regulations and regulatory sandboxes that provide space for experimentation. For example, Ofgem announced an expansion of its regulatory sandbox service to support innovative services and business models contributing to the decarbonisation of energy. There is an opportunity for regulators across sectors to build on this work.

RECOMMENDATION 11

Creating a stronger innovation ecosystem for net zero and distributing the benefits: Government should use new models of challenge-led innovation to tackle the net zero challenge, with a greater focus on digitalisation.

These should consider a balanced portfolio of risk, including 'high-risk, high-reward' research, and should be based on a lean structure in which qualified research and innovation programme leaders appointed on a fixed-term basis are given greater discretion over the programmes that they select.



Conclusion

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Conclusion

Tackling climate change and achieving the UK's commitment to net zero emissions by 2050 requires transformative changes across the economy and society. Digital technology can be an enabler of this change. The UK is a unique position to drive this change, building on its world-leading digital technology research and vibrant tech start-up ecosystems.

To create a future in which the power of digital technologies is harnessed to support planetary wellbeing and human flourishing, action is needed to support the development and deployment of digital-enabled solutions to urgently reduce emissions at scale. This will require integrating data and digital technologies into decision-making processes to better manage systems, as well as developing trustworthy technologies to support decision-making and providing guidance on their implementation. To develop the core digital capabilities for net zero and new applications of digital technologies to a range of sectors, it will be necessary to develop stakeholder-led solutions to key challenges, highlight areas of opportunity and direct funding to them. The public, private and third sector need to devise ways to facilitate working across research domains and collaborations across sectors in order to develop and deploy creative technology solutions. There is also a need to bridge discussions across technology and policy communities, so each can better understand the interventions needed to facilitate further action.

Wider policies on sustainability will have a large influence on steering the development of data-enabled applications and the degree to which digital technologies will serve the net zero target. Digital technologies are tools and the context in which they are developed and deployed will determine the extent to which they will help fix climate issues. Wider policies will help set a direction towards greener ways of living and working, and digital technologies will help achieve the rapid change needed to achieving it in a timely manner.

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Appendix

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Appendix

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Achieving 'net zero' from buildings and digital technology: what's the vision?
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