THE ROYAL SOCIETY

Computing for net zero:
how digital technology can create a 'control loop for the protection of the planet'

In brief

Digital technology could play an important role in the transition to a low carbon world by enabling emissions reductions across the global economy and limiting the emissions created by computing itself*. In particular, there is an opportunity to bring together governments, academia, industry and the third sector to create a 'planetary digital twin' or operational 'control loop for the protection of the planet'. Used responsibly, this could simulate, optimise and transform economic activity to minimise emissions and maximise efficiency.

INSIGHTS

- 'Computing for net zero' could play an important role in global, regional and national net zero strategies.
- The digital technology sector's power use and carbon footprint, including embodied emissions, should be proportionate to its benefits.
- Greater coordination globally on data standards, quality and regulation will enable relevant data to be collected, shared and used with confidence, supporting better quantification of greenhouse gas emissions as well as applications to reduce them.
- Collaborations between governments, academia, industry and the third sector can create 'digital twins' of natural and economic systems at city, regional, national and ultimately global levels to minimise emissions, inform trade-offs and promote sustainable development. Such digital twins would also allow governments to explore 'what-if' scenarios and impacts of interventions.
- Global collaboration is critical to create a trusted governance framework for computing and data infrastructures for net zero systems. This includes the ability to inspect such systems, supported by transparency in reporting of emissions; stakeholder participation, with applications that work for everyone; and resilience of critical digital infrastructure.
- The tech sector should lead by example, with tech companies publicly reporting their energy use and direct and indirect emissions, as well as optimising their use of renewable energy.
- Progress can be underpinned by an improved global research and innovation ecosystem, using a 'digital commons' of free or low-cost technology components, facilitated by governments.
- Wide availability of technology and data will underpin global coverage, and capacity building will be essential to ensure no one is left behind.

* This briefing is based on the Royal Society's report *Digital technology and the planet: harnessing computing for net zero* (see: https://royalsociety.org/-/media/policy/projects/digital-technology-and-the-planet/digital-technology-and-the-planet-report.pdf, accessed 23 March 2021), as well as input from international experts.

1. Context

Digital technology has revolutionised the way we live and work, with more than half of the world's population now online and using mobile phones, and this is projected to grow to two-thirds by 2023[1]. Modern Artificial Intelligence (AI) algorithms enable computers to learn patterns from vast volumes of data, helping drivers plot delivery routes and doctors diagnose diseases. Simulations of physical assets, known as 'digital twins', already improve productivity and efficiency in factories.

In terms of climate change, the digital technology sector has been the subject of mixed headlines. The industry's carbon emissions have attracted attention as internet traffic has grown rapidly. On the positive side, there are applications of digital technologies that support emissions reductions, such as AI consolidating routes in logistics and avoiding empty delivery vans. Tackling climate change is a complex issue that calls for a systems approach. Already, climate models that simulate Earth's natural systems running on supercomputers, have been central to the growing understanding of climate change[2].

There is increasing recognition of the potential of digital technology to make a wider contribution to the international effort to address climate change. This starts with 'green computing', or making the sector's own footprint proportional to its usefulness, and goes on to the much larger contribution digital technology can make in supporting and driving emissions reduction, or 'computing for net zero'. This will require establishing confidence in the systems, 'trustworthy computing for net zero'; and supporting the research, development and deployment required, 'innovation for computing for net zero'.

2. Green computing

The digital technology sector's carbon footprint should be proportionate to its benefits. As an example, the cryptocurrency Bitcoin is estimated to consume around 80 – 100 TWh as of March 2021, as much power as Norway[3,4]. Regulators around the world could act to prevent disproportionate energy use by requiring environmental impact analyses for digital activities, as is now common practice for major infrastructure investments.

Building new systems to optimise emissions will entail new components, sensors, networks, computing and storage facilities, all of which generate emissions. However, if the net impact is to help reduce overall emissions to net zero, this would constitute proportionate use of data and digital technology. Industry-led studies suggest that applying existing digital technology ambitiously[5] across sectors could help deliver around one-third of the reductions required by 2030 for a pathway to a global average temperature of well below 2°C[6, 7], estimates that merit further investigation.

The carbon footprint of the tech sector is difficult to quantify. Estimates vary from around 1.5% to 6.0% of annual global greenhouse gas (GHG) emissions, depending on how the sector's boundaries are defined[8, 9, 10, 11]. Emissions from devices, networks and data centres arise from manufacturing and power use – with a roughly equal split between the two for user devices[10].

Recent analysis shows that the energy demand of data centres has hardly increased over the past decade although global internet traffic increased on average 30% a year, and compute power rose considerably[12]. This is in large part explained by improvements in computing efficiency and in data centre management practice. Migrating tasks and storage to 'cloud' computing is a potential emissions-saver. Improved transparency of emissions data is needed to fully evaluate the benefits[13, 14].

As a larger fraction of global population is set to connect to the internet, demands on the tech sector are set to grow. Driving energy efficiency further will be important and require research and innovation, for example on ways to reduce energy requirements of algorithms, and new forms of hardware. It will also be critical for the transition to green energy to happen worldwide.

Large technology companies are major users of renewable energy (see Box 1), which lowers the carbon footprint from their data centres. Some are even starting to use intelligent computing platforms that enable them to schedule energy intensive tasks to run at times of peak renewable energy generation, a development that promises to maximise the use of clean energy[15, 16]. To enable progress monitoring and maintain trust, all companies should provide transparency about the details of their renewable energy use.

BOX 1

Big tech pledges small footprint

With technology businesses now among the world's largest, their commitments to carbon neutrality are significant, as will be measures to monitor their performance against the commitments. Microsoft plans to be carbon negative by 2030 and remove all the carbon the company has emitted from the environment by 2050[37]. Apple reports that it uses 100% renewable energy at its facilities and has a programme to transition its suppliers to renewable electricity and reach carbon neutrality for its entire footprint by 2030[38]. Google claims to have become carbon neutral in 2007, that it uses 100% renewable energy and aims to be carbon-free by 2030[39]. Amazon has pledged to be climate-neutral by 2040 and power all operations with renewable energy by 2025[40]. However, assessing the progress of the sector towards these targets will require transparent access to good quality, reliable data about its emissions and energy use.

> Assessing the sector's progress towards decarbonisation requires access to data about its emissions and energy use.

3. Computing for net zero

Digital technologies offer tools to support a better-connected system, and to yield overall solutions that are better than the sum of its parts.

3.1 Data and digital technologies are increasingly applied to tackle climate change

Beyond the tech sector itself, computers are increasingly being used in a range of applications that help reduce emissions.

For example, accurate weather forecasting, data from local and remote sensors, including satellites, plus connectivity and interfaces on mobile phones provide tools for precision agriculture. If given the means to use these tools, farmers around the world could make decisions about crop choice, irrigation, application of fertilisers and harvest timings. The Global Partnership for Sustainable Development Data is exploring how digital tools can support sustainable development goals (SDGs) more widely. One example of its work has been the Africa Regional Data Cube, using 17 years' worth of satellite imagery to monitor water extent, land use and land degradation[17].

In energy, modern AI methods can be used to predict peak of power consumption demands, as well as predict peaks of solar and wind energy generation based on accurate forecasts of weather patterns[18].

3.2 Digital twins can support a systems approach for the planet

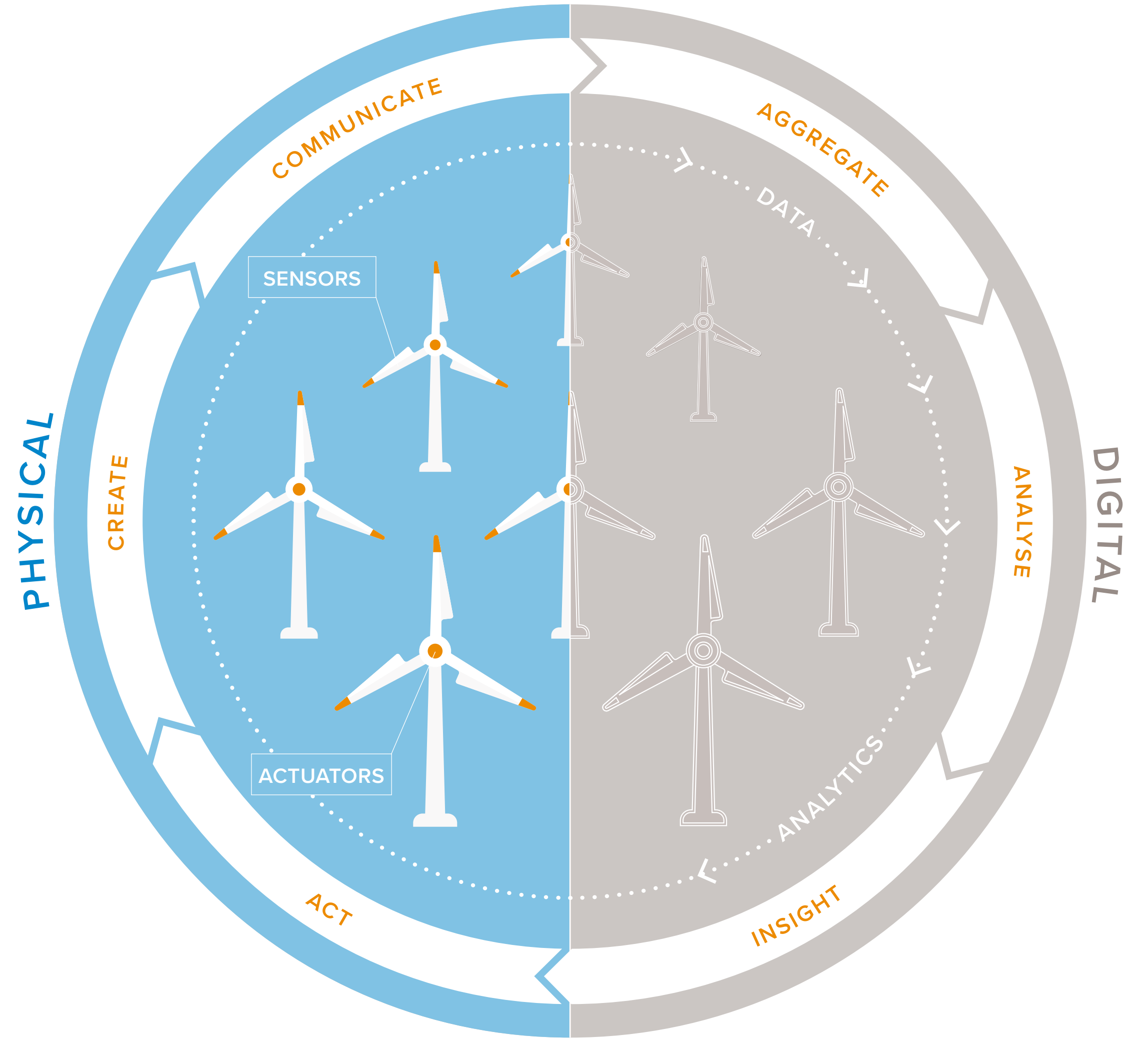
One of the key challenges in tackling climate change is that there are interdependencies in the Earth system, with co-benefits and trade-offs in pursuing different SDGs. Data and digital technologies offer tools to support a better-connected system, and to yield overall solutions that are better than the sum of its parts.

Systems providing adaptive controls have been used in flights for decades, demonstrating the benefits from equipping physical objects with models that can adapt their behaviours. Similarly, one of the digital capabilities with promising applications for the planet is 'digital twinning'[19]. In twinning, data from multiple aspects of a process are gathered, typically from sensors, and used to create a computer simulation of the activity. Such simulations can help calculate the optimal solution subject to given goals and constraints. This information is then used to control the actual operation. Hence an operational 'control loop' is created, with data fed from the real-world activity to the simulation and the outcome of the simulation used to adapt and improve the real-world process (see Figure 1).

FIGURE 1

Turbine twins

Wind farms are becoming test-beds for digital twins as operators investigate ways to maximise efficiency in a sector growing at around 20% per year[41]. For example, GE Renewable Energy has built several digitally twinned projects to show how the technology can be used. The farms begin as computer models that simulate local wind conditions and enable engineers to configure the most efficient pole height, rotor diameter and turbine output. Once the turbines are spinning, sensors inside each turbine monitor parameters from the yaw of the nacelle to the torque of the generator and the speed of the blade tips. Digital twins use physics models built into their software to process data, simulate options and suggest improvements[42, 43]. Improved maintenance means the infrastructure can last for longer.



There are huge challenges in accessing the data necessary to create a comprehensive control loop for the protection of the planet.

Digital twins make it possible to establish feedback loops to monitor, understand, optimise and reduce GHG emissions in many sectors:

- In electricity grids, digital twinning can support power grids increasingly dominated by renewable energy, by managing numerous decentralised sources (see Figure 1) and switching on back-up power when needed.
- In planning and development, twins can help in siting assets. For example, Google's project Sunroof[20] uses Google Earth and machine learning to provide free solar energy mapping, helping guide the installation of solar panels.
- In cities, digital twins are demonstrating their value in pursuing net zero, and serving as pilots for national and supranational digital twins. Digital twins such as the London Building Stock Model can be used to identify needs for improvement, taking into account a range of data from built form to the socio-economic background of occupants[21]. Similarly, digital twins of Singapore, Shanghai, Beijing, Amaravati (India) and Dubai have been created to help improve urban design and city life. Several countries are developing their digital twinning capability. The UK's National Digital Twin programme aims to improve how infrastructure is built, operated and decommissioned.
- In transport, virtual replicas of transport networks can enable public authorities and fleet operators to optimise flows[18].
- In climate monitoring, digital twins, combining satellites and ground-based observation, can play an increasing role in providing more accurate, dynamic information on actual GHG emissions, as opposed to those extrapolated from energy generation or consumption.

On a global scale, and provided adequate coordination, such local, national and sectoral digital twins could be progressively integrated into a 'planetary digital twin', or 'a control loop for the protection of the planet' (see Figure 2). This would help monitor, simulate, understand, optimise and transform economic activity and complement the models that simulate the response of the climate.

Such initiatives are already starting to take shape. Over the past two decades, the concept of Digital Earth, 'a multi-resolution, three-dimensional representation of the planet' has inspired research and collaboration in support of global sustainable development[22,23]. The European Union recently announced it would implement by 2030 a high precision digital model of Earth, DestinE, to model both human and natural activity[24]. By 2025, the platform could integrate 4 – 5 digital twins helping public sector users develop, monitor and assess the impact of proposed environmental and climate policies.

Creating such a digital ecosystem at scale is a technical challenge, requiring an effective architecture and systems for managing interfaces[25]. And in terms of access to data, while rich data streams are being created by satellites, for example, there are huge challenges in accessing the data necessary to create a comprehensive control loop for the protection of the planet. Building a multi-sectoral, planetary digital twin will also require burden-sharing arrangements to ensure that all countries in both Global North and South can participate and benefit.

3.3 Data infrastructure for net zero

A planet-level digital twin requires data on an unprecedented scale from across economic sectors in order to optimise activity to reduce emissions. A roadmap to make such data available might include the following initial steps:

- **Supporting more effective use of existing data.**
  Existing datasets can be repurposed, and made more accessible, with public and independent institutions taking a lead. National statistics bodies can assume a major role. For example, Tanzania's National Bureau of Statistics has developed reports on e-waste[26] and climate change statistics[27]. There is also a need to enable access to proprietary data that is valuable to tackle the climate emergency (see Box 2)[28].
- **Characterising the need for further data.**
  Gaps in data need to be identified and processes designed to fill them. Aggregated data or proxy data might be sufficient, and the benefits and costs of new data collection need to be analysed on a case by case basis. The generation of reliable synthetic data could present another alternative.
- **Combining multiple sources of data.**
  Common standards are needed to enable data to be merged. For example, satellite data combined with on-the-ground measurements can help track emissions from power plants or urban areas.
- **Building capacity in existing data infrastructures.**
  High-quality repositories are required worldwide to replicate the role of data stores such as the UK Met Office Informatics Lab or Japan's Space Weather Forecast Center. Different forms of data institutions could be explored[29].
- **Ensuring data 'readiness' is essential[30, 31].**
  The GO FAIR initiative[32] to encourage data that is actionable using machine learning says that data should be: findable, for humans and communities; accessible, including via authentication and authorisation; interoperable, capable of being integrated with other data; and reusable, or able to be combined in different settings.

BOX 2

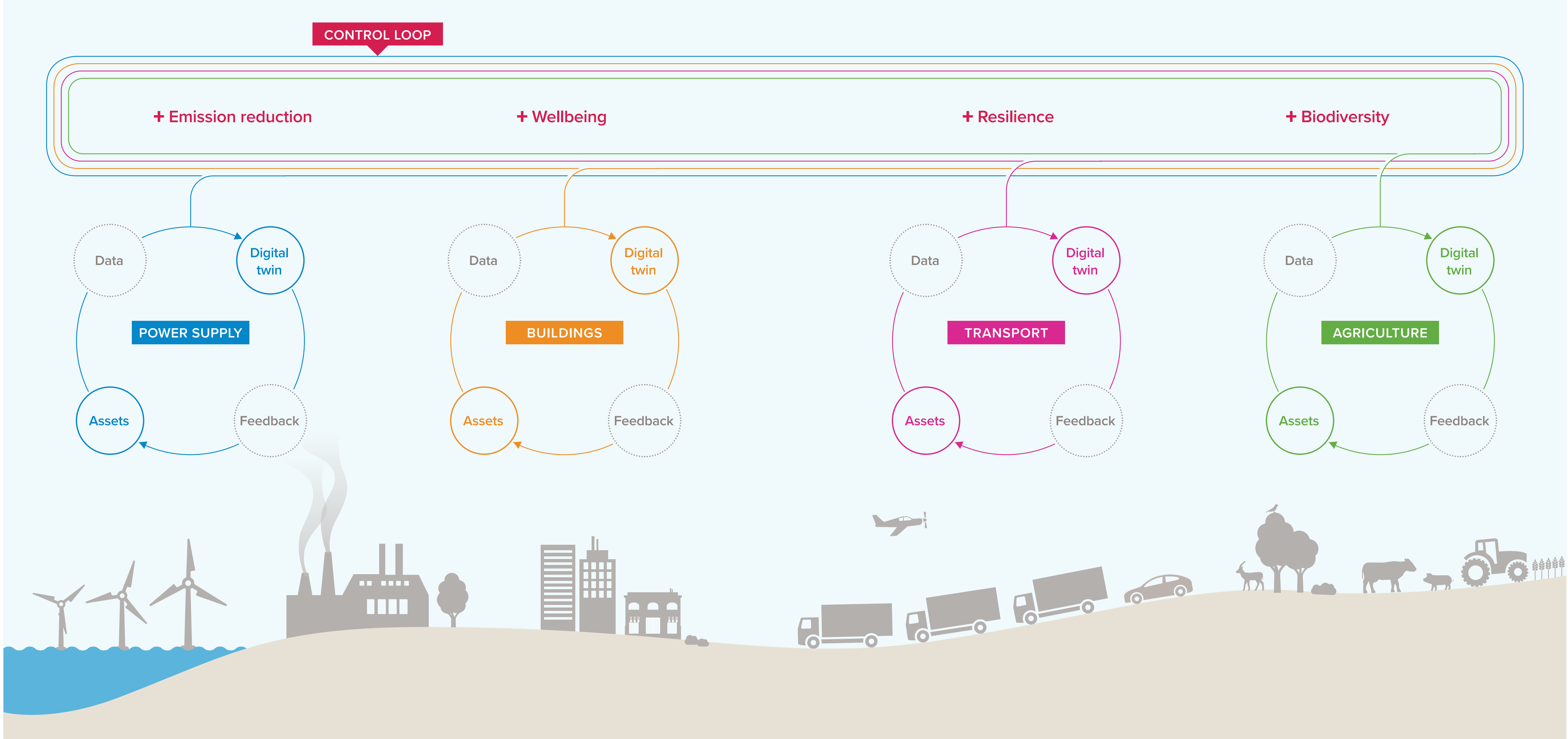
Lockdown data reveals net-zero challenge

The 2020 COVID-19 pandemic provided a unique opportunity for climate scientists working with data to demonstrate the scale of the effort required to achieve net-zero. Combining real-time data on economic activity related to 97% of global carbon emissions, they found a 26% average decrease in national emissions in the first few weeks of widespread lockdown. The researchers estimated the overall annual decrease in global emissions to likely be 4.2 – 7.5%, comparable to the annual rate needed over the next three decades to limit the global average temperature rise to well below 2°C. The project demonstrated what could be achieved by using multiple sources of publicly available data, from US steel output to Chinese coal production and UK smart meter statistics[44]. However, researchers also faced challenges in identifying and accessing some of the datasets. A future in which these data types are made more widely available offers new opportunities to monitor global emissions.

FIGURE 2

A control loop for the protection of the planet

Virtual representations of physical assets – digital twins – can be created to run simulations and improve the planning and operations of these assets. Linked together to establish a 'control loop for the protection of the planet', they could help find global solutions to tackle climate change, biodiversity loss, and other 21st century challenges.



4. Trustworthy computing for net zero

Several factors must be considered to build trust as data is gathered for computing for net zero:

- **Resilience and cybersecurity**
  Computing for net zero forms part of critical infrastructure and needs to be fully cybersecure to retain public confidence. Interoperability, longevity and security will need to be built in from the start. The internet has demonstrated the importance of redundancy for resilience, with multiple options that avoid dependence on single routes or hubs.
- **Participation**
  Digital technologies, in this and other contexts, can raise public concerns over privacy. This is the subject of ongoing work by the Global Partnership on AI[33]. Data may also be sensitive due to its strategic value, and adequate technical and legal safeguards, together with governance arrangements such as codes of conduct[34], will need to be developed. Involving all stakeholders in the design of computing for net-zero systems, as well as associated policies, will help build the trust required[35].
- **Contestation**
  People should be able to challenge outputs from digital systems, for example by interrogating data logs. 'Explainability' is important on multiple levels, be it in verifying outcomes, meeting regulatory standards or safeguarding against bias[36].

5. Innovation for computing for net zero

Creating a planetary digital twin is an ambitious global research and innovation mission. A collective effort across governments, academia, industry, public sector and civil society – committing funding, data, skills and computing facilities – is required for rapid progress.

Governments can use their procurement power to commission technologists to create a 'logical infrastructure' of components to create multiple applications. This infrastructure would comprise a 'digital commons' of building blocks available free or at low cost for developers. Financial incentives, such as a royalty for user uptake, could encourage innovators to develop solutions. Experimental packages could be trialled, with successful ones being scaled up incrementally.

Such a platform could be facilitated through a network of community interest laboratories run through collaboration between governments, tech companies, wider industry, small innovation enterprises and researchers in academia and institutes. Such a community would need to be encouraged to develop its own culture and mission, potentially with its own charter and legal status, independent of the countries and companies that support it. Challenge-based funding and aspirational targets could be set to incentivise breakthrough innovation and attract talent into public sector research programmes.

There is now an opportunity to take the first steps towards building such an international research and innovation ecosystem as part of a wider programme to create a trusted control loop for the protection of the planet.

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This briefing is one of a series looking at how science and technology can support the global effort to achieve net zero emissions and adapt to climate change. The series aims to inform policymakers around the world on 12 issues where science can inform understanding and action as each country creates its own road map to net zero by 2050.

To view the whole series, visit **royalsociety.org/climate-science-solutions**
To view contributors to the briefings, visit **royalsociety.org/climate-solutions-contributors**

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