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Digitalization and the Anthropocene

Felix Creutzig,[1,2] Daron Acemoglu,[3] Xuemei Bai,[4]
Paul N. Edwards,[5] Marie Josefine Hintz,[2,6,7]
Lynn H. Kaack,[7] Siir Kilkis,[8] Stefanie Kunkel,[9]
Amy Luers,[10] Nikola Milojevic-Dupont,[1,2]
Dave Rejeski,[11] Jürgen Renn,[12] David Rolnick,[13,14]
Christoph Rosol,[12,15] Daniela Russ,[16]
Thomas Turnbull,[12] Elena Verdolini,[17,18]
Felix Wagner,[1,2] Charlie Wilson,[19] Aicha Zekar,[2]
and Marius Zumwald[2]

[1] Mercator Research Institute on Global Commons and Climate Change, Berlin, Germany; email: creutzig@mcc-berlin.net

[2] Sustainability Economics of Human Settlements, Technical University Berlin, Berlin, Germany

[3] Department of Economics, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

[4] Fenner School of Environment and Society, Australian National University, Canberra, Australia

[5] Center for International Security and Cooperation, Stanford University, Stanford, California, USA

[6] ICLEI—Local Governments for Sustainability, Berlin, Germany

[7] Hertie School, Berlin, Germany

[8] Scientific and Technological Research Council of Turkey, Ankara, Turkey

[9] Institute for Advanced Sustainability Studies, Potsdam, Germany

[10] Microsoft, Seattle, Washington, USA

[11] Environmental Law Institute, Washington, DC, USA

[12] Max Planck Institute for the History of Science, Berlin, Germany

[13] School of Computer Science, McGill University, Montreal, Canada

[14] Mila—Quebec AI Institute, Montreal, Canada

[15] Haus der Kulturen der Welt, Berlin, Germany

[16] Sociology Department, University of Toronto, Toronto, Canada

[17] Department of Law, University of Brescia, Brescia, Italy

[18] RFF-CMCC European Institute on Economics and the Environment, Euro-Mediterranean Center on Climate Change, Milan, Italy

[19] Environmental Change Institute, University of Oxford, Oxford, United Kingdom

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Keywords

Anthropocene, digitalization, artificial intelligence, planetary stability, leverage points, trust

Abstract

Great claims have been made about the benefits of dematerialization in a digital service economy. However, digitalization has historically increased environmental impacts at local and planetary scales, affecting labor markets, resource use, governance, and power relationships. Here we study the past, present, and future of digitalization through the lens of three interdependent elements of the Anthropocene: (*a*) planetary boundaries and stability, (*b*) equity within and between countries, and (*c*) human agency and governance, mediated via (*i*) increasing resource efficiency, (*ii*) accelerating consumption and scale effects, (*iii*) expanding political and economic control, and (*iv*) deteriorating social cohesion. While direct environmental impacts matter, the indirect and systemic effects of digitalization are more profoundly reshaping the relationship between humans, technosphere and planet. We develop three scenarios: planetary instability, green but inhumane, and deliberate for the good. We conclude with identifying leverage points that shift human–digital–Earth interactions toward sustainability.

Contents

1. INTRODUCTION

Anthropocene: proposed geological epoch characterized by the fundamental impacts of human activities at the Earth-system level; currently under review for addition to the Geological Time Scale

Human industrial activities are now the dominant influence on myriad Earth system parameters. Their influence has proven so great that they have heralded a new epoch in geologic history: the Anthropocene (1–4). Digitalization has changed and accelerated human influence, and given its extraordinary enabling power, it will likely define the Anthropocene's future path to a considerable extent (5). Academic literature and the interested public increasingly focus on the environmental footprint of digital devices, services, and infrastructures, epitomized by the case of Bitcoin, a blockchain-based, decentralized cryptocurrency created by highly energy-intensive, virtual mining operations (6). The direct energy impacts of these and other specific digital applications are important, but they should not obscure the wider question of how information and communication technologies (ICTs) and digitalization have shaped and continue to shape the coupled trajectory of human civilization and planetary states.

Digitalization: megatrend changing societies and economies via use of digital technologies

What do we mean by an ICT? Broadly defined, an ICT is any means of storing, processing, or transmitting units of information. It could be anything from a Sumerian tablet in the distant past to a supercomputing facility in the present. Digitization is a relatively recent form of information storage, in which information is reduced to a sequence of zeroes and ones. Digitalization refers to the widespread deployment of digital ICTs (7).

A comprehensive understanding of the role of ICTs and digitalization in the evolution of global social and environmental dynamics is still missing. In this review, we help close that gap by investigating how ICT and digitalization have acted as major drivers of change throughout human history, and how they shape our present and future trajectory in relation to three criteria for life in the Anthropocene: environmental protection and planetary stability, human agency and its governance, and equity and access.

First, we provide select historical examples of predigital ICTs to illustrate common themes emerging from their development and use. These include (*a*) increased efficacy in monitoring, measuring, and managing processes; (*b*) the enabling of expanded political or economic control over both time and space; and (*c*) novel production and consumption opportunities associated with an increase in resource consumption. Our premise is that early ICTs were precursors of digitalization not only in terms of their technological history but also in terms of their role in mobilizing ever larger societal and material systems—from ancient city-states to colonial empires to the globally interconnected economy.

Second, we review the channels through which digitalization is currently influencing the natural environment and social systems, either directly, for example, through energy consumption of server infrastructure, or indirectly, by affecting labor markets, the distribution of and access to resources (i.e., inequality), social interaction, and systems of governance. We emphasize the long tail of resource extraction in which ICTs require an increasingly diverse set of material resources (such as rare earth elements), but we also consider the mechanisms and potentials for digital technologies to alleviate environmental impacts. We also examine how digitalization can be viewed as a double-edged sword that affects the environment through new consumption opportunities on the back of deeply problematic practices toward social and behavioral control in increasingly surveilled online economies and networks.

Third, we turn to the future to explore three qualitative scenarios characterizing possible relationships between observed digitalization trends and human–Earth system trajectories. We distinguish between different combinations of directed and undirected changes in technological efficiency and digital infrastructures. We conclude that if global cooperation succeeds in restricting resource use and stabilizing Earth systems within planetary boundaries, then digitalization could support a rapid transition to a low-impact, high–service level economy. But this depends critically on strong convergence between hitherto divergent policy agendas around digitalization, climatic stability, and biosphere protection and the transition to just and fair standards of living. The design of digital infrastructure and platforms will be equally important in shaping resource demands, equity, and human agency in the Anthropocene.

2. THE PAST: INFORMATION AND COMMUNICATION TECHNOLOGIES AND THE ENVIRONMENT FROM SELECT HISTORICAL PERSPECTIVES

The histories of ICTs are instructive not only for understanding their foundational role in transforming societies and modes of social interaction but also for appraising their crucial function in

IRRIGATION IN SUMER

As the first scriptural civilization, Sumer serves as a prime example of the relationships among ICTs, stratified sociopolitical systems, efficient resource management, and environmental consequences (10). Sumer developed in the southern part of fertile Mesopotamia, between the Euphrates and Tigris rivers. Statehood emerged in the third millennium BCE, characterized by a centralized government with the ability to collect taxes and draft men, women, children, and slaves to work on the limited amount of fertile land controlled by an elite (11–13). The state managed the collection and storage of abundant wheat, a surplus that in turn supported the introduction of cuneiform scripts, an elaborate accounting system used for the economic and administrative records of an expanding state administration. This information system emerged from the needs of a redistributive economy and later gave rise to the development of a writing system capable of representing language (10, 14). Cuneiform script was also used to keep, record, and manage larger irrigation systems through so-called farmers' instructions. This was not the case in smaller, local systems (15). According to Sumer records, the elite also used cuneiform script to convey messages that could not be entrusted to verbal communication by messengers (16). This finding suggests that early communication technologies were relevant to the co-evolution of larger-scale projects that required informational records to increase the productivity and governance of land use. Associated centrally organized canal projects helped make resource provision more efficient and plentiful but were also instrumental in one of the first well-recorded incidents of anthropogenic environmental destruction at ecosystem scale: the salinization of soil in southern Mesopotamia (17).

the human-led modification and exploitation of the environment. The extraction, modification, use, and disposal of natural resources have always been closely tied to, and mediated by, certain forms of ICTs that were available at specific times and in specific cultures. Media technologies altered human–environment interactions, forming a dominant part of the so-called technosphere: the human-created fabric of industrial technologies, infrastructures, energy flows, and social institutions that increasingly interact with and function at a level equivalent to that of other Earth system spheres (8, 9). Development and use of the first scripts in Sumer in the third millennium BCE show that this very early ICT played an enabling role in the expansion of political and managerial control over large-scale systems (agricultural irrigation), with associated gains in overall productivity and collective agency but also resource overexploitation (see the sidebar titled Irrigation in Sumer).

Fast-forwarding to the extraction and use of coal during industrialization more than four millennia later demonstrates, again, that information control technologies enabled the design and operation of large-scale systems, but with adverse impacts on both resource consumption and human agency. ICTs were integral to the industrialization of the British and then other European economies in the eighteenth and nineteenth centuries, based on mechanization and the use of coal for power. Early industrialization relied on literacy and an expansive knowledge economy enabled by novel ICTs such as accounting and printing techniques, supporting further technological advances and the spread of technical literature (14, 18–20). While some scholars have argued that innovation was the key ingredient of the Industrial Revolution (21), environmental historians refute this argument, pointing to coal's energy density, its relation to colonial expansion, and its role in fueling recursive cycles of investment and the exploitation of labor (22–25). Coal was uniquely positioned to break the "Malthusian deadlock" that constrained all kinds of growth before 1800, including that of knowledge (26).

Technosphere: technological systems with own networked agency that impact the earth system

There is no simple relation between coal use and knowledge in any given industrializing society. Recent historical statistical analyses have found that industrialization increased the literacy of a small section of the workforce, while a greater number of workers were seemingly deskilled as a result of the mechanization of labor (27). Industrialization dynamics in England in the year 1800 reveal that while the presence of steam engines increased the share of skilled workers (indicating migration as much as increased skills), in places it negatively affected primary education and the literacy of women in particular (28). Over the longer term, however, coal-powered industrialism increased the availability of wealth and created the conditions for more universal access to education (28).

From a resource use perspective, coal-powered industrialism enabled the creation of infrastructure ranging from road and rail networks to—most importantly—the electrical grid, which was essential to the later development of digital infrastructure (29). These developments were intimately connected to the production of information. New information devices and metrological processes enabled the efficient and balanced operation of power machinery (30). As an example, indicator mechanisms were first patented by engineer John Southern (1758–1815) and used by engineer James Watt (1736–1819) as a self-registering mechanism that allowed the pressure of Watt's newly invented rotary engines to quantify and display their recorded motive power. This was vital to ensuring that the load (i.e., the machinery connected to an engine) was matched to the power of the engine (31). Another information technology was the centrifugal steam engine governor, which could be connected to a motive rotary engine to regulate its speed. Thanks to a wind-driven reciprocal mechanism, at a certain speed the governor would cut off the supply of steam to the engine. The governor was an early feedback mechanism regulating the rate of coal combustion (32).

With electrification, the challenge of balancing power to load became ever more closely entwined with the generation of information. Calculations of voltage, current, and resistance enabled the construction of electrical systems, but they could not ensure efficient operation. Load management, developed between 1880 and 1910, used information technology to ensure maximum utilization of the system (33). Meters, indicators, and load diagrams (which recorded the variation of electricity use over time) documented the economic state of the system and can be seen as a feedback mechanism that informed supply management. These technologies and methods were vital for the expansion of central stations into regional and national electric systems during the period 1890–1920. Analog models of the electrical grid were even more important progenitors of the modern computer. The MIT electrical engineering lab's differential analyzer and the network analyzer are key examples from the 1930s (34). Electricity meters also helped fund the interconnection and spread of the grid (35) and later underpinned control engineering and the so-called Second Industrial Revolution (36).

Coal, of course, is a major contributor to anthropogenic climate change. Information-based control technologies of both devices (e.g., steam engine regulators) and production systems (e.g., manufacturing plants and industrial facilities) enabled strong productivity gains during industrialization. However, from a resource use perspective, energy consumption increased as scale effects more than offset efficiency improvements. In the 1930s, the resource economist Erich Zimmermann (1888–1961) noted that increased efficiency in the amount of coal needed to generate a kilowatt hour of electricity had not resulted in overall savings (37). It had reduced the growth rate in coal consumption for each kilowatt of power, but it had increased the scale of national electrical energy use by lowering the unit cost of a kilowatt hour—a demonstration of the efficiency paradox (38). This key historical case shows that increased process efficiency enabled by digital technologies will likely prove insufficient to ensure sustainable resource use (39).

The first half of the twentieth century saw increased activity in the creation of mechanical computers (40), the legacy of more than a century of interest in the mechanization of mathematical and statistical problems and their logical computation. Analog calculators and differential analyzers, which worked with mechanical relays, could be used only for specified and highly limited problems. A step change occurred in the second half of the 1940s, when logical computer design, mathematical information theory based on binary digits, improved vacuum tube design and, soon thereafter, semiconductor physics, as well as the formulation of cybernetics as a new scientific paradigm, all converged onto the technological trajectory centered around electronic (i.e., light-speed) computation.

Microelectronics spurred the rise of the digital age, encouraging decisive developments in the military–industrial complex of the Cold War, in business, accounting, trade, planning, and material design. Digital signal processing proved to be, according to retrospective economic analysis, a general-purpose technology: widely used, capable of ongoing technical improvement, enabling innovation in varied application sectors (41). All kinds of applications of these digital machines ensued, from numerical meteorology to government statistics and aircraft design, forming even a new rationality and governmentality (42, 43). Artificial intelligence (AI) was introduced in the mid-1950s to extend the possibilities of representing and processing knowledge with machines. The rise of computer networks—especially ARPANET (Advanced Research Projects Agency Network) and basic internet technologies such as packet switching and the TCP/IP protocol (44)—gave rise to a new form of data-intensive networked intelligence.

This historical trajectory from the 1940s to today is part and parcel of the inherent dynamics of the Great Acceleration (45). The computer revolution coincides with the inflection point of the Great Acceleration around 1950, which—not coincidentally—is also considered to be the geological beginning of the Anthropocene (46, 47). The relationship between electronic computing and a measurable impact on Earth strata is surprisingly direct. The Anthropocene Working Group tasked with identifying the possible chronostratigraphic base of the Anthropocene considers plutonium fallout from nuclear weapons testing as one of the most promising candidates for demarcating the onset of the epoch of humankind. The design of the first atomic bomb and then the hydrogen bomb would have been impossible without the aid of electronic computing and the accurate simulation of fission reactions that computers allowed for (48). Therefore, one of the most striking anthropogenic impacts on the global environment, directly indicative of the Anthropocene epoch, was enabled by modern ICTs.

The direct economic impact of ICT was at first sporadic but then gained traction after the revolution in consumer electronics in the 1970s and 1980s. While the effect of digitalization is difficult to assess with standard econometric analysis, the fundamental impact of the general-purpose technology electronic computer on changing, multiplying, and globalizing economic activities and markets—for both production and consumption—cannot be underestimated (40). Digital infrastructures have enabled scaling and network effects to spread across economic sectors, driving growth in both material and energetic turnover (4, 49). The introduction of digital means of processing and circulating information accelerated the extraction and mobilization of natural resources, the production of goods and their often wasteful consumption, the globalization of trade and finance, and, in turn, the anthropogenic impacts of these activities on the Earth system (4, 50, 51).

Today, human agency is scarcely conceivable without the myriad transistors that are photolithographed onto integrated circuits in order to switch between two basic electrical states. Such basic manipulations at the micro level have massive effects at the macro level. The historical result of this technological step change in ICTs—one might call it the Great Digitalization—is apparent not only in economic output and growth but also in how culture, politics, and science have reoriented themselves to support the structural formation of a digitally orchestrated technosphere (7).

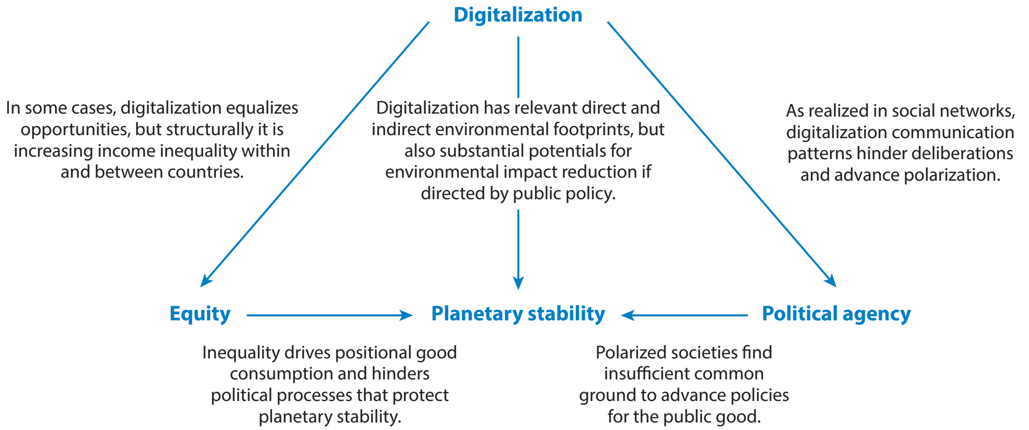

Figure 1

Relationships among digitalization, equity, political agency, and planetary stability. Digitalization influences climate change and planetary stability, for example via energy demand of data centers but also via digital and artificial intelligence applications that reduce greenhouse gas emissions and environmental impact (see **Table 1**). Digitalization also influences social equity both within and between countries. Algorithms are instrumental in creating polarization and in shaping political opinion in social media. High levels of inequity and polarization reduce the feasibility of consensual climate policies and hence are indirectly relevant for planetary stability.

3. THE PRESENT: DIGITALIZATION AND ITS IMPLICATIONS FOR ENVIRONMENT, AGENCY, AND EQUITY IN THE ANTHROPOCENE

Common themes from these historical accounts of ICTs persist into the current digital age. These themes include efficiencies in the monitoring and managing of processes and systems, expanding political or economic control, uneven distributional impacts on labor and agency, and novel forms of production and consumption associated with increased aggregate resource use. In this section, we examine digitalization through a present-day lens against our objectives for the Anthropocene: equity (Section 3.1), human agency (Section 3.2), and the environment and associated planetary stability (Section 3.3). These objectives are interrelated (**Figure 1**) and hence should be considered part of the larger dynamics of the Anthropocene.

3.1. Equity and Distributional Effects

If digitalization in the Anthropocene should benefit humans and the environment, its socioeconomic consequences also need to be understood, particularly through the lens of equity and in low- and middle-income countries in the Global South, where growth margins in unsaturated markets for digitalization are higher. Digitalization is developed unevenly both within and across countries globally. A world map of the International Telecommunication Union's ICT Development Index (**Figure 2**) shows strong differences in digital development across low-, middle-, and high-income economies. Countries in Africa and South America with lower incomes tend to have lower digital development.

Digitalization also changes how value is added and distributed at different stages of the value chain within and across economies (e.g., through increasing the value share of services relative to physical products) and how trade patterns evolve (e.g., through decreasing transaction costs in logistics) (52). The diffusion of digital technologies thus raises distributional concerns, given its

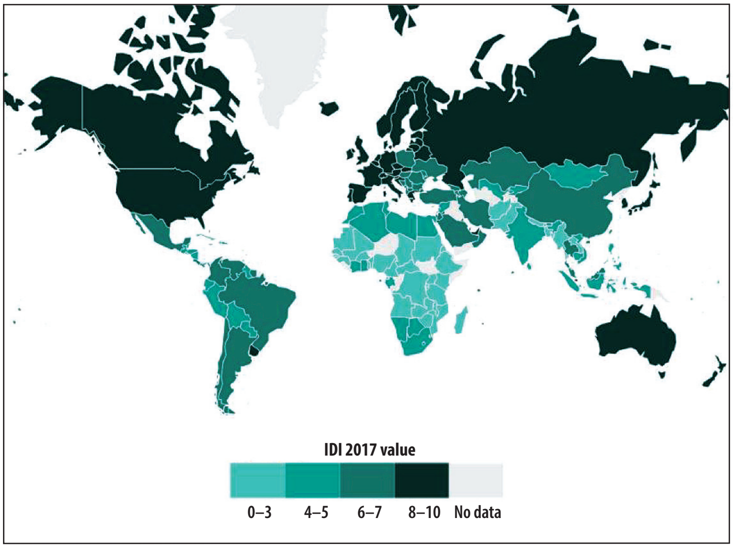

Figure 2

The International Telecommunication Union's 2017 ICT Development Index (IDI 2017). The index is based on 10 indicators: landline subscriptions, international internet bandwidth, households with a computer, households with internet access, individuals using the internet, fixed broadband subscriptions, active mobile broadband subscriptions, mean years of schooling, secondary gross enrollment, and tertiary gross enrollment. Figure adapted with permission from International Telecommunication Union data (**https://www.itu.int/net4/ITU-D/idi/2017/index.html#idi2017map-tab**).

implications for labor demand and wages, the digital divide (inequality of access), and the unequal burden of environmental degradation falling on low- and middle-income countries.

Is digitalization good or bad for developing countries? On the one hand, digitally enabled businesses are expected to create catch-up possibilities for low- and middle-income countries in the global digitalized economy. The internet economy of the early 2000s, for instance, raised expectations that the phenomenon of professional business services outsourcing (53, 54) would create jobs in countries such as India with favorable business conditions (e.g., a large workforce with a good command of the English language for programming tasks). Similar expectations now exist around the gig economy, with small service jobs being done online by so-called click workers in countries such as the Philippines (55). On the other hand, digitalization is labor saving through automation in factories and more efficient organization of business processes (replicating patterns observed during historical industrialization; see Section 2). This may create problems for low- and middle-income countries seeking employment opportunities for young and growing populations. Simultaneously, the decreasing importance of labor relative to capital weakens low- and middle-income countries' competitive advantage created through cheap and abundant labor (56). Moreover, developed countries currently profit from digitalization. For instance, 83% of ICT manufacturing value added is created in China, Taiwan, USA, South Korea, and Japan, and 74% of global robot installations are similarly concentrated in only five countries: USA, China, Germany, South Korea, and Japan. None of the 10 biggest online platforms globally are from South America, Africa, or other regions in the Global South.

Empirical evidence on how digitalization affects labor markets is still limited and focuses largely on developed countries. Early studies focusing on computers, ICTs, and software applications suggest that their introduction has displaced some jobs but also created new ones (57). In the USA, the recent stagnation of labor demand can be explained by an acceleration of automation, particularly in manufacturing, and a deceleration in the creation of new tasks (58). Employment in occupations requiring routine tasks as well as the number of workers with low computer literacy has declined, but workers whose more complex abstract and manual tasks cannot be easily performed by machines have benefited. As a result, wages have polarized (57, 59, 60). Stagnation or a drop in real wages in the lower two-thirds of income groups, especially among males, has been documented, while the top one-third of workers experienced continued income growth (61). These changes resulted in higher inequality within OECD countries, affecting predominantly the middle class (62). Adoption of robots in the US local labor market has been found to displace workers (63), but no strong evidence of a similar displacement effect has been found in preliminary analyses of Europe, where robotization has had either a limited or zero impact on employment, although it has affected the composition of the labor force in terms of skill (64–66). A potential explanation for this difference may lie in labor market regulation, which differs significantly between the two regions.

ICTs' material footprint also has major social implications (67, 68). Rare earth elements and metals such as tantalum, tungsten, gold, tin, and cobalt are key ingredients of electronics components such as batteries or semiconductors (69). These critical raw materials are extracted by workers primarily in artisanal mines in the Global South, including Congo, Ghana, Peru, and Chile (67). Communities near mines or disposal sites are adversely affected, as are local ecosystems through air and river pollution as well as deforestation (70). Mining of both rare earth elements and metals, as well as recycling processes, is characterized by hazardous and inhumane working conditions, with a lack of health and safety equipment leading to high exposure of workers to mine dust and toxic substances (69, 71). Mining workers are also placed at risk through exposure to hazardous chemicals and injuries and deaths from falls, rockfalls, accidents involving machinery and mine collapses, fatal mudslides, and landslides (72, 73). Mining operations servicing the ICT sector are associated with forced labor practices, including child labor, excessive working hours, low wages, lack of social protection, discrimination against migrant workers, humiliating disciplinary actions, and (sexual) violence (73–77).

There are further equity considerations on the consumption side of digital products. The mobile phone is already one of the most equitably accessible technologies globally, with a Gini coefficient of 0.20 (where 0 is perfect equality and 1 is perfect inequality), compared with the Gini coefficients for GDP (0.43), TVs (0.49), electricity (0.50), cars (0.65), and the internet (0.66) (78). Mobile phones as end-user ICTs provide access to information, networks, education, financial services, and expertise that support livelihoods, social relationships, and basic need fulfillment. Reliable, affordable, and accessible digital infrastructure is a basic requirement for life in the Anthropocene. The digital divide currently falls along fault lines of geography, gender, age, and development. Currently, 72% of the world's urban population has internet access at home, compared with 37% in rural areas (79). Just over half (51%) of the global population uses the internet, but this percentage masks the disparity between developed regions (87%) and least-developed countries (19%), as well as between males (55%) and females (48%). The COVID-19 pandemic deepened the digital divide, marginalizing those without digital technologies, skills, mindsets, and infrastructure access as public services and employment rapidly moved online (80).

Overall, digitalization is associated with a concentration of value creation in several hubs, mostly in North America, Europe, and East Asia, and with a polarization of income within countries. Digitalization may still benefit countries in the Global South, but this will likely require a continuation of the emancipation of countries from global structures of dependency. Shifts in public policy are also required to counter within-country wage imbalances and social inequities arising from digitalization and its material footprint.

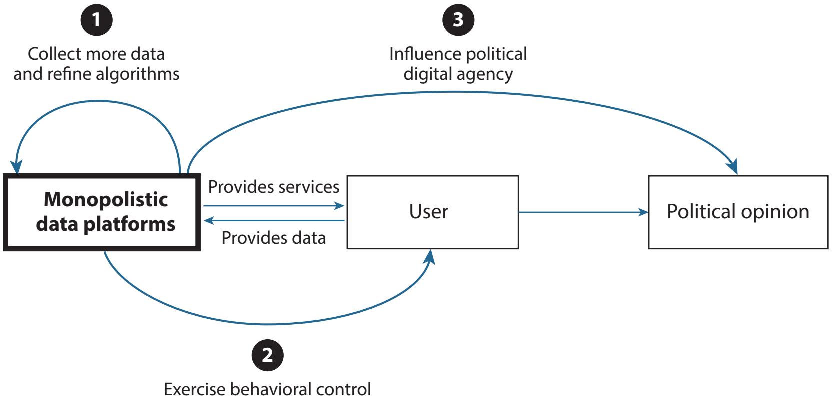

Figure 3

Three interrelated concerns regarding how monopolistic social media influence democratic processes: (❶) monopolistic data accumulation, (❷) exercise of behavioral control, and (❸) influence on political agency.

3.2. Data, Democracy, and Governance

The current digital age is founded on a massive expansion in the generation, flow, processing, and storage of data. Data accumulation by social media and other data-based internet firms enables service provision while creating an important training resource for AI across many different applications. Social media platforms and digital services realize important social benefits, such as (*a*) helping to form political and social organizations, (*b*) giving voice to identity communities, (*c*) realizing and supporting local and community networks, (*d*) diffusing information (as well as misinformation) rapidly, and (*e*) offering new opportunities for digital governance and public service. However, data accumulation also raises significant concerns, including (*a*) unregulated monopoly power of firms in data-based markets, (*b*) behavioral control networks designed to maximize profits (surveillance capitalism) or to maintain and increase state power, and (*c*) threats to democracy through social media polarization of political opinion (**Figure 3**).

First, data are a resource, and their accumulation by a firm, especially if unshared, can lead to monopoly power (81). Data and, more broadly, knowledge are by their nature nonrivalrous goods that can be (re)used by many actors in creative and productive ways, leading to both intended and unintended innovations. For instance, the microblogging service provider Twitter has granted researchers frictionless and automated access to subsets of their data, enabling various types of research with social benefit, such as rapid assessments of disaster damages of natural catastrophes (82) or of relationships among weather, climate impacts, and expressed sentiment (83). Social media data also contribute to research on solutions for urban sustainability (84, 85). However, innovation is limited if access to data is restricted or monopolized (81, 86). Monopolistic digital service providers maintain advantages of scale by acquiring niche innovators (supported by the current venture capital system) and by investing heavily in research and development to ensure competitive advantage over new entrants (87).

Second, commodification of accumulated data allows firms to exert behavioral control over users under a new economic paradigm termed surveillance capitalism (88). Digitalization thus extends the expansion of political and social control observed with historical ICTs into the private sphere through the social networks and digital devices that connect the globe. At its core, surveillance capitalism is the ability to accurately predict the future behavior and personal attributes of individuals by exploiting data that reveal their preferences, behavior, choices, and beliefs (89, 90). Such predictions allow firms to nudge people into staying on their platforms, thus generating more data, as well as profits from the sale of both insights and data to other firms interested in targeting individuals with personalized advertising (88). For the critical human agency dimension of the Anthropocene, data surveillance and commodification can endanger democracy or increase state power. For example, the introduction of a social credit system by governments demonstrates how data surveillance is used to enable "data-informed economic and social planning on a national scale" (91) in which individual behavior is controlled by tailored incentives and punishments.

Third, social media platforms threaten democratic governance (92). Over time, their algorithms have learned that emotional messaging is most efficient in retaining users. Facebook users are statistically likely to join polarized communities (echo chambers), seeking confirmation bias, and ignoring dissenting information, thus reducing social trust across ethnic, political, or religious groups (93). Such echo chambers have unintended consequences, as emotional messaging polarizes individuals, strongly reduces space for mutual understanding, and, as a result, negatively affects the fundamental principles of democracy (92). Emotive and targeted messaging can also influence elections (94) and reduce social trust in journalism (95).

3.3. Digitalization's Environmental Footprint and Improvement Potential

Digitalization expands human control over the Earth system by reducing friction in communication and by enabling supervision of large-scale and complex technological systems, compounding the dynamics of the Great Acceleration (45) and the impact of humanity on the Earth's ecosystems. Generally, ICTs' impacts are grouped into direct effects, which result from the life cycle of digital hardware and infrastructure, and indirect effects, which result from the repercussions of certain uses of these technologies including behavioral and systemic effects (96–98).

Direct impacts of digital technologies include greenhouse gas (GHG) emissions, water consumption, and material use associated with the production, use, and end of life of devices and computer infrastructure (96, 99). For example, digitalization affects the environment through the extraction and mining of raw materials for myriad ICT devices, ranging from laptops and smartphones to servers and networks (67). Electrical and electronic equipment accounts for a sizable share of total global material flows in copper (30%), lead (85%), tin (47%), antimony (50%), and rare earth metals including indium, gallium, germanium, and ruthenium (all >80%) (100). With the growing number of devices in use and the increase of expectations regarding their processing power, digital devices are designed to have short life spans, leading to a high amount of electronic waste (e-waste). E-waste is the fastest growing waste stream globally. Only 17% of the estimated 53.6 Mt of e-waste produced globally in 2019 was collected and recycled (101). Sustainable procurement practices, extended producer responsibility, and so-called circular electronics designed for increased life span, repair, and reuse are potential solutions, yet they remain far from mainstream (71).

Indirect impacts of digital technologies on energy and resource exploitation can also lead to increased emissions and environmental effects (i.e., the scale effect) (97, 98, 102–104). Digital markets are intentionally designed to enable a convenient, frictionless purchasing process with strong consumer appeal (7). This process increases aggregated consumption, echoing the efficiency paradox shown in historical accounts of ICT usage. As people spend more time using digital services, they reveal information about their individual preferences that can be used to expand product and service offerings. By matching heterogeneous consumer preferences to a broader range of supply alternatives, digitalization helps create a market of niche, specialized products—a long-tail effect—that further expands consumption opportunities.

Digitalization also holds a substantial but unrealized potential for stabilizing the planetary trajectory. Routes for unlocking this potential include (*a*) efficiency improvements in computational infrastructure, (*b*) rapid innovation in data science and AI applied to sustainability challenges, and (*c*) knowledge to inform strategies to manage the planet in a sustainable way.

The first route focuses on digitalization's direct energy demand particularly in data centers (98). Digital technologies consume large amounts of energy—more than 7 EJ in 2018 (97, 105). The development of certain very large deep neural networks generated as much as 313 metric tons of CO_2 (106). The number of global data center workloads and compute instances (virtual machines that run workloads) grew by 550% between 2010 and 2018 (107). Yet, data center providers countered this increasing demand by substantial efforts to increase efficiency. Resulting energy demand increased only by around 6% from 2010 to 2018 and is now estimated at around 1% of global electricity consumption (107). Deliberate engineering efforts were undertaken to make data centers more efficient, renewable energy sources are increasingly used for data center operation, and approaches for using waste heat for other purposes exist (108). If efficiency improvements can keep pace with computing needs, and if data center operators employ a 24/7 renewable energy supply (109) and leverage their position to pioneer energy technologies (110), then the direct GHG emission footprint of data centers could be contained.

The second route encompasses the application of digital technologies toward improving the sustainability of engineering systems and exploiting an untapped efficiency potential (111). Notably, the fields of AI and machine learning (ML) are making a concerted effort to determine how these techniques can contribute to the greater good, particularly sustainability goals (112) including climate change mitigation and adaptation (104, 113). **Table 1** summarizes relevant applications. Nonetheless, digitalization alone will be insufficient; complementary policy instruments, research and development investments, and infrastructure provision will be needed to create strong incentives for emission-reducing digital applications (104, 114).

The third route relates to the role of digitalization in providing knowledge to inform strategies to manage the planet in a sustainable way (115). Digital technologies, data and computer science, and ML play an important role in climate and Earth sciences, as well as in other sustainability fields (116). They are also instrumental for informing policy and decision makers on how they can address environmental challenges (113). Digital technologies enable raw data collection with sensors, satellites, and the like at an unprecedented scale and granularity that are driving scientific discovery. For example, remote sensing approaches combining ML techniques and satellite images have been used to map and help plan the extension of solar photovoltaic installations at a global scale (117).

4. THE FUTURE: PATHWAYS AND LEVERS

Turning to the future, we sketch three pathways for digitalization in the Anthropocene, varying in their performance against our evaluation criteria of agency, equity, and planetary stability. We then identify a set of measures that provide tentative direction toward the most optimistic scenario. Finally, we point to four system-level leverage points underpinning a transition toward a stabilized planet with full human agency and social equity (**Table 2**).

4.1. Conceptualization and Scenarios

To the best of our knowledge, no current conceptualization of decarbonization pathways explicitly accounts for the impacts of digitalization in the Anthropocene. This is a major gap, because digitalization clearly has stark consequences for (*a*) planetary stability (energy, GHG emission, material use, and land demand), (*b*) social equity (the distribution of costs and benefits associated with digital technologies, including through labor markets), and (*c*) political agency (participatory

Table 1 Exemplary digital applications for reducing GHG emissions

End use sector	Quantitative evidence	Contribution of digitalization	Systems perspective, risks, and societal impacts	References
Residential energy use (e.g., nudges, feedback, information)	2–4% reduction in global household energy use possible	Effective in combination with monetary incentives, nondigital information	New appliances increase consumption.	119–121
Smart mobility (shared mobility and digital feedback for ecodriving)	Reduction in shared cycling, shared pooled mobility, and ecodriving Increase in ride hailing, ride sourcing	Apps together with big data and machine learning as preconditions for new shared mobility	Ride hailing increases GHG emissions, especially due to deadheading as well as scale effects.	122–124
Smart cities (use of digital devices and big data to make urban transport and building use more efficient)	30% reduction in a smart city scenario due to targeted climate-mitigation interventions, including AI-based low-carbon urban planning, shared pooled mobility, etc.	Big data analysis necessary for optimization of service provisioning systems	Efficiency gains offset by rebound effects Privacy concerns linked with digital devices in homes	125, 126
Agriculture (precision agriculture through sensors and satellites providing information on soil moisture, temperature, crop growth, and livestock)	Very high potential for variable-rate nitrogen application Moderate potential for variable-rate irrigation	ICTs enable farmers to increase yields, optimize crop management, and reduce fertilizers, pesticides, feed, and water. Increases labor productivity	Digital divide growing quickly, especially between modern and subsistence farming Privacy and data may erode trust in technologies.	127–129
Industry (IoT)	Process, activity, and functional optimization increase energy and carbon efficiency.	Increased efficiency 1.3 Gt CO_2 equivalent estimated abatement potential in manufacturing	Optimization in value chains can reduce wasted resources.	113, 130
Load management and battery storage optimization	Reduces supply capacity required for peak demand Shifts demand to align with intermittent renewable energy availability	Accelerated experimentation in materials science with AI Forecast and control algorithms for storage and dispatch management	Facilitate integration of renewable energy sources Improve utilization of generation assets Systemwide rebound effects possible	131–133

Abbreviations: AI, artificial intelligence; GHG, greenhouse gas; ICT, information and communication technology; IoT, Internet of Things.

Table 2 Characteristics and outcomes of three pathways for digitalization in the Anthropocene

Scenario	Characteristics	Outcomes
Planetary destabilization	High increase in automation/surveillance High increase in consumption High increase in extraction with limited efficiency gains	Biodiversity destruction and climate change High risks for well-being and habitat High risks for democracy Loss of social trust Medium agency High inequalities Medium increase in knowledge
Green but inhumane	High increase in automation/surveillance High decrease in consumption High decrease in extraction with high efficiency gains	Resource and biodiversity preservation, climate change mitigation: limited risks for well-being and habitat Limited agency: loss of democratic rights High inequality in power (but equality in consumption) Limited increase in knowledge
Deliberate for the good	Limited automation/surveillance High decrease in consumption High decrease in extraction with medium-high efficiency gains	Resource and biodiversity preservation, climate change mitigation: limited risks for well-being and habitat High agency: high social trust and participation Healthy democracy Medium inequalities High increase in knowledge

control in digitalization). On a meta level, institutions, values, and social organization will shape how digitalization influences the Anthropocene.

From this conceptualization of the interactions among the digital system, Earth system, and human societies, we discuss three illustrative future pathways that span the possibility space for digitalization and decarbonization in the Anthropocene, namely (*a*) planetary destabilization, (*b*) green but inhumane, and (*c*) deliberate for the good. **Figure 4** provides a stylized representation of each pathway's likely implication for GHG emissions. Planetary destabilization refers to a world in which digital technologies increase efficiency but also result in system-level increases in energy demand, runaway resource consumption and planetary destabilization, increased centralization of knowledge and power incompatible with democratic deliberation, and increased inequality. Green but inhumane refers to a world in which digital technologies such as AI and big data provide opportunities to steer and support technological change away from fossil fuels and toward the rapid deployment of renewable and energy-efficient technologies, while avoiding overconsumption and redeployment of technologies, but with human agency increasingly constrained. Deliberate for the good refers to a world in which AI technologies alongside decentralized computing structures are used efficiently and effectively, with trusted data practices and high levels of distributed agency.

4.1.1. Planetary destabilization. The planetary destabilization scenario is conceptualized as a continuation of current trends, with digitalization mostly ungoverned, increased consumption of digital and physical services, resource extraction, and centralization of knowledge and power (134–137). In this context, the digital system would exert indirect control over human societies (138) as well as increased control of the Earth system through the expansion of resource extraction enabled by highly automated (digital) technologies (139). The rebound and scale effects of digitalization continue to dominate and increase in scale and magnitude (140). The likely environmental outcomes of such a scenario are rapid resource exhaustion, high threats to biodiversity, and increases

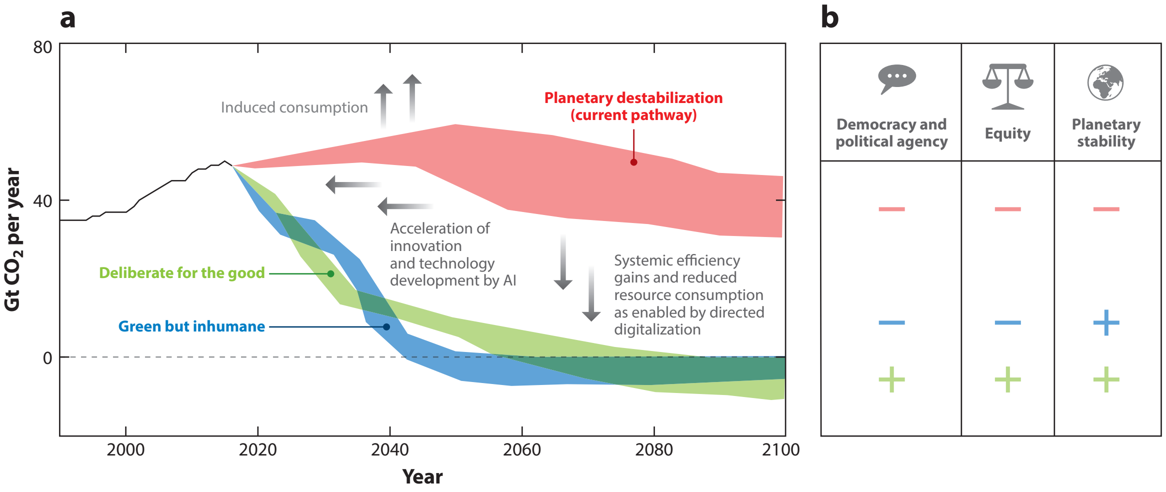

Figure 4

Three illustrative pathways for digitalization in the Anthropocene with divergent outcomes for planetary stability, social equity, and political agency. (*a*) The funnels represent possible GHG emission ranges in each pathway, and the arrows indicate the main determinants of GHG outcomes. (*b*) The icons and table depict positive (+) and negative (−) implications for planetary stability, social equity, and political agency in each pathway. The GHG emission trajectories for the current planetary destabilization pathway (*red*) follow baseline scenarios from the IPCC (118), while those for the deliberate for the good (*green*) and green but inhumane (*blue*) pathways are speculative and should be interpreted only qualitatively. The outcomes of the three additional dimensions are qualitative assessments by the authors based on the material provided in this review. Abbreviations: AI, artificial intelligence; GHG, greenhouse gas.

in global CO_2 emissions leading to severe climate change. Strong feedback loops causing high risks to human well-being and habitat would also materialize. Other plausible social outcomes of this scenario include increased inequalities induced by widespread automation of production systems, loss of social trust, a deepening digital divide (unequal access to digital infrastructure), and resulting high risks for liberal democracies. This possible future world is characterized by low agency. While state control is limited, allowing for agency in principle, digitalization is not used to increase citizen inclusion and participation in political affairs but rather to polarize opinions, including via the spread of misinformation. Data accumulation and the resulting knowledge generation increase across applications, including those that help accelerate the exploitation of planetary resources. Social inequity balloons, driven by rent seeking in physical resources and by data companies, while the vast majority have to endure climate change, rapid planetary environmental degradation, biodiversity loss, and instrumentalization as data objects subject to behavioral control. Given these outcomes, this scenario is clearly the most pessimistic and least desirable, as it leads to destabilization of both the Earth system and human societies.

4.1.2. Green but inhumane. Instead of enabling growth in production and consumption, digitalization could in principle be used as a way to sharply reduce both. Realizing the green but inhumane pathway means directing technical progress toward maximizing efficiency in terms of resource use, including through rapid deployment of efficient technologies (107, 141, 142), alongside strong social and political action to mitigate or avoid rebound effects. In terms of energy, this pathway benefits from Earth being an open thermodynamic system into which streams 175,000 TW of solar energy. Therefore, depending on how ICTs are configured and where the energy used to power them comes from, it could be possible to impose thermodynamic order at the scale of the Earth system (143). This scenario also entails the use of digital technologies to centrally control populations, and thus limit their resource consumption, through approaches such as big data–driven surveillance and control (144). If directed toward high-efficiency gains, digitalization may provide a 10–20% reduction in GHGs while enabling high shares of intermittent renewables in electricity networks and tackling the major control challenges integrating demand, storage, and variable supply. Limitations on individual consumption may be operationalized by a strong surveillance state through the widespread deployment of granular monitoring systems that provide high-frequency data streams, which, together with AI technologies, could enable effective and continuous population control (145).

Although such a pathway may dramatically reduce the human footprint on the Earth system, the green but inhumane scenario comes with large adverse effects for human societies. Agency would be highly constrained because of the loss of democratic rights and a lack of distributed information in a digital system focused mostly on controlling populations and processes as opposed to fostering knowledge systems. Social inequity may be high, dominated by a small cyborg ruling elite/dictatorship.

4.1.3. Deliberate for the good. Neither of the first two scenarios provides desirable outcomes for human societies, highlighting the need for an explicit consideration of which kinds of digital systems can enable and promote a high level of human agency while providing capacities to safeguard the Earth system. A pathway that could achieve such objectives would make efficient and effective use of AI technologies, accompanied by decentralized computing structures, data trusts, and high levels of distributed agency (146). The theory of change in this scenario posits decreasing environmental impacts via both increased efficiency and reduced demand that would stem not from population control but rather from self-determination in a context of effective knowledge systems that foster empathy, accountability, and collaboration (147). The social outcome of such a system would include high social trust and citizen participation within healthy democratic processes (148).

4.2. Steering Digitalization Toward Public Purpose

To change the trajectory of digitalization and resource use from one of planetary destabilization toward one that deliberates for the good, worldwide regulations and policies must take responsibility, redirecting dynamics toward low levels of resource use and GHG emissions, social equity, and digital agency. Currently, secular digitalization trends and global sustainability policy agendas are largely disconnected. Their alignment is a major challenge for multilevel governance. This implies activity from the local to the transnational scale through policies, regulations, coalitions, initiatives, activist demands, consumer preference, corporate leadership, experiments, urban innovations, and so on. Such redirection relies as much on prohibitions and boundaries as on desirable action (149).

In the environmental domain, constraints on digitalization are warranted to limit accelerated resource-intensive consumption. In economic analysis, efficient restraint is achieved by charging current transactions with current and future environmental costs. Current estimates suggest a social cost of carbon of approximately \$100–300 in 2030, with higher values for a 1.5°C climate stabilization goal and little reliance on CO_2-removal technologies (150, 151). At a 2020 level of carbon intensity (152), this estimate would translate into a 1–3% increase in purchase price for the average Amazon package (ignoring the costs of carbon embedded in the production of consumption items and the non-CO_2-related harms of planetary boundaries via mining, land use, etc.). Fiscal instruments have been proposed to shift blockchain verification protocols away from energy- and CO_2-intensive proof of work (153). Altogether, carbon pricing alone, while necessary, will not suffice to maintain planetary stability. A larger-scale shift toward biosphere stewardship is needed—a transformation of our relationship with nature to one that conserves, restores, and enhances its benefits for people and planet (154), implying "a fundamental shift in governance from reducing human pressures only, to managing nature actively to promote multigenerational human wellbeing" (154). Inter alia, such a shift would translate into protecting irrecoverable carbon stocks in vulnerable terrestrial and coastal ecosystems. The protection of carbon stocks in turn may prohibit mining of minerals, which would pose a material constraint on the expansion of digital products.

Digitalization efforts should be concentrated where they bring the highest value (see also Section 3). There are many practical examples of shifting rules, regulations, practices and mindsets to ensure a healthy contribution of digitalization in the Anthropocene (**Table 3**). First, regulations and circular economy practices can limit ICT product obsolescence, reduce e-waste, ensure end-of-life producer responsibility, and increase mineral recovery and recycling rates to dramatically reduce extractive activity (155). Second, an energy proportionality test can be applied to new digital applications to embed planetary stewardship principles in digital product and service development as well as to guide regulators toward constraining excess (156). Third, regulators managing access to urban space (e.g., city authorities), energy infrastructure (e.g., national utilities), and public services (e.g., e-health, e-education) can extract open data commitments from digital service providers as part of their social license to operate. Such commitments should include data on the direct and indirect behavioral impacts of digital services. This way, rebound and intensification effects can be measured and managed. Open data can also support agile zero-carbon urban planning practices (125). Digital technology has already contributed significantly to reducing the casualties/impacts of natural or other hazards/disasters, such as floods (157). Fourth, methodologies linking digital applications to emission impacts can normalize carbon labeling of ICT use and digital services such as video streaming (158). Google's inclusion of carbon emission rankings in search results and travel recommendations is a powerful example of aligning choice architectures with sustainability goals. But standardizing carbon labeling of end-user services also enables informed regulation, such as discriminatory incentives (feebates) and dynamically improving best-in-class standards (e.g., the Japanese Top Runner Programme for energy efficiency).

In the social equity domain, a key direction is regulating the data-based monopoly power of big tech companies. This could be achieved by mandating data sharing as a function of market power (81). Related but not identical is taxing away the data rents obtained in particular by multinational businesses that rely on national infrastructures for their platform solutions, obtaining (eventually global) (quasi-)rents from data-based transactions while avoiding taxes by shifting nominal revenues to low-tax destinations.

The introduction of market-based digital service taxes (DSTs) is an appropriate and adequate tool for more efficient and fair distribution (159) as well as an adequate tool to reduce the digital divide and expand universal digital access. DSTs aim to ensure that countries obtain taxing rights over the profits of data-based multinational companies that locally sell products, collect data, and target advertisements at local consumers. A DST-based redistribution complements a resource use–based redistribution, such as national redistribution of carbon pricing revenues as climate dividends, a progressive redistribution that will reduce the global poverty head count by six million in 2030 (160), and international support of climate mitigation and biosphere stewardship programs by transferring funds intended both to support the introduction of local carbon pricing and to reduce the capital costs of low-carbon investments in developing countries (161, 162).

Strategic public and private investment in infrastructure development can rapidly increase the 57% share of the global population able to access the internet on a daily basis, thus addressing the inequities described in Section 3.2. Alongside access to digital infrastructure, digital skills and

Table 3 Mapping of the solution space for environmental, equity, and agency domains

Domains	Main areas of action	Solution space options	Examples and initiatives	References
Environment	Regulations and circular economy practices to avoid pressures on natural resources, including carbon sinks and mining pollution	Durable designs, legislation against planned obsolescence, redesigned value chains for closed-loop production, zero e-waste circular economy	Laws mandating durability and repair, targets for recycled content in new electronic products, electronics as a service	155, 168, 169
	Energy proportionality test for comparing digital applications by incurred energy and emissions	Promoting digital efficiency of end-users and leaner codes possibilities	Regulators and authorities developing guidance on energy proportionality, pay-for-performance programs, including digital options	156, 170
	Open data commitments to measure and manage rebound and intensification effects	Use of open-source datasets by regulators in the scope of their social license to operate	Opportunities for zero-carbon urban spaces, energy infrastructure, and public services	125, 171, 172
	Mainstreaming carbon labeling of ICT use and digital services	Best-in-class standards, carbon footprint and life cycle inventories	Carbon emission rankings, user analytics on impacts in digital services in science-based targets	158, 173
Social equity	Regulating data-based monopoly power to increase social equity	Mandating data sharing as a function of market power or taxing away data rents with taxation systems for the digital economy	Data sharing obligation or market-based digital service taxes on digital services and presence	81, 174, 175
	Improving digital capabilities and governance	Strategic investment to address the digital divide	Human capital development for digital skills and literacy	176
Agency	Empowering digital subjects to become active agents of their data	Redesigning data infrastructures through data cooperatives or ensuring decentralized and secure private data	Data exchange infrastructures and other initiatives to direct digitalization for public purpose	163–167

Abbreviations: e-waste, electronic waste; ICT, information and communication technology.

ESTONIA'S DIGITAL GOVERNMENT

Estonia is a front-runner in providing digital government services. Its data exchange infrastructure, X-Road, allows citizens to access all public and private services via one infrastructure while keeping specific data distributed in a noncentralized way across diverse servers and ensuring data exchange via distributed ledgers (165, 166). The digital government builds on central institutions that are committed to the digital infrastructure. A core task is the provision of the Estonian eID. Overall, this design not only saves substantial administrative resources but also increases social trust (165, 167).

literacy should be embedded in school curricula worldwide as central to human capital development in the Anthropocene. An understanding of data, control, algorithms, programming, and rights in the technosphere should sit alongside critical awareness of ideas, arguments, perspectives, and media as basic tenets of good citizenship. Monopolistic digital platforms should be regulated as such, with clear public purpose goals and structures defined to ensure that their activity serves collective goals, fosters participatory governance, strengthens democratic institutions, and improves digital governance.

In the agency domain, the current trend toward a total data-based control mechanism, provided by ubiquitous location-based tracking and control of all messenger content (e.g., the EU e-Privacy Derogation, which allows providers of email and messaging services to automatically search all personal messages of each citizen), requires counterbalancing and specific policies that make keeping private data private the default. While the EU General Data Protection Regulation is well motivated, it fails to make digital subjects active agents of their data. A specific goal is to shift extreme data-based power and control from a few multinational enterprises and agencies back to users and individual data providers.

One way forward would be to redesign data infrastructures via data cooperatives that collectively organize and manage users' data both for the public good and, subject to active agreement, for commercial usage (163, 164). Another way forward would be to provide data exchange infrastructures like Estonia's X-Road, which keeps private data decentralized and secure (see the sidebar titled Estonia's Digital Government). Cities like Barcelona, Boston, and Paris; communities of interest (e.g., open source movements, citizen science); and coalitions and pressure groups (e.g., Sustainability in the Digital Age) also exemplify the increasing effort to take control of digitalization for public purposes.

4.3. The How: Digitalization and System Change

Digitalization has the ability to influence what Meadows (177) highlighted as some of the strongest leverage points over system dynamics: those that alter information flows and controls, rules of the system, the power structures and dynamics that uphold existing rules, and the mindsets that define them. The societal transformations driven by digitalization demonstrate the power of these levers, as digitalization has radically altered information flows and controls throughout society, influencing consumption, political and economic influence, equity, and trust. Digitalization has also created opportunities to push the most influential set of levers of system change highlighted by Meadows: rules, structures, goals, and mindsets (**Figure 5**).

The first leverage point is the reformalization of rules and feedback, as discussed in the preceding section. Important options include mandatory data sharing in big tech and with urban/local administrations as condition for license; default data management as data commons or data trusts; a requirement for circular electronics designed for increased life span, repair, and reuse; and the

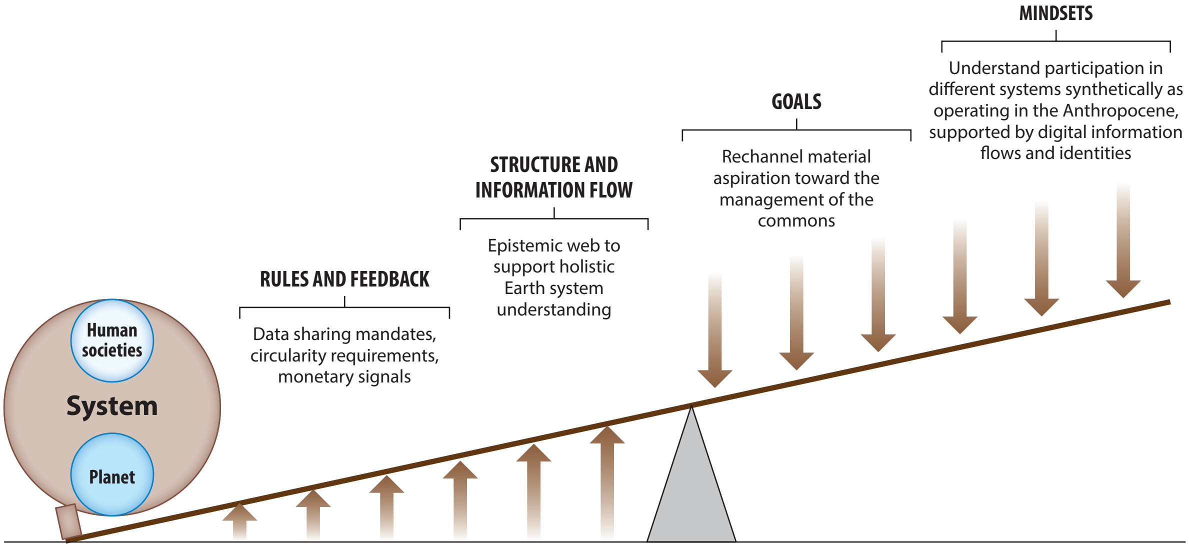

Figure 5

Leverage points of digitalization to steer the coupled human–technological/digital–planetary system toward planetary stability, equity, and maintenance of political agency, as seen through the lens of digitalization. Figure adapted and expanded from Reference 149.

use of tax incentives and price signals as feedback to steer digital use cases toward low environmental impact.

The second leverage point is the modification of structures and the creation of new ones. Digitalization can play a crucial role by offering a holistic data-based Earth system understanding (116), which would translate into an informational governance that leverages the use of information to drive innovations in governance mechanisms and institutions (149, 178). The World Wide Web has become an important medium for driving digitally enabled social change and activism. It has considerably lowered the cost and changed the form of participation in collective social actions, which no longer demand the copresence of its protagonists in time and space. The Web has also enabled fundamentally new forms of social interaction, in particular new ways of spontaneously organizing and coordinating collective actions and ways of reacting to their results. The Web's impact on the ability of collective action to address the global challenges of the Anthropocene, however, will critically depend not only on the social opportunities that the new technologies afford but also on the knowledge it makes available to these actions. In other words, the Web's impact will depend less on its agility as a social web than on its qualities as an epistemic one. An epistemic web would be characterized by balanced ownership and control of knowledge; public access provides content, connectivity, and the means of controlling the quality and reliability of the represented knowledge. Here, existing public knowledge infrastructures and representations are not only realized as a common good (necessary for survival in the Anthropocene) but also further developed into a web offering coproduction, open sharing, and public appropriation of knowledge, shifting agency toward the users of the system (149). Crucial examples include, technically, carbon labeling methodologies and reporting and, procedurally, the closing of the digital divide not only as an equity-respecting goal but also to include the voices of the previously marginalized, ranging from information housing to indigenous communities, within the global epistemic web.

The third leverage point is the resetting of goals, at both individual and societal levels, away from aspirational resource-intensive consumption (e.g., private cars, mansions) toward positive

INFORMATION AND ENERGY: A MUTUAL RELATIONSHIP

It is possible to imagine a machine that uses information to generate power (called Szilard's engine). Information storage is a reduction in a given system's disorder (entropy) that requires the provision of external energy. This means that the intervention of an intelligent being, an information processor, in a closed thermodynamic system could never decrease the entropy in that system without subverting the second law of thermodynamics (182). From this perspective, human knowledge creation can give rise to "local and temporary islands of decreasing entropy," but this has an associated energy requirement (183). The result is Szilard's Paradox, the idea that within a closed thermodynamic system, information-driven ordering processes will always consume more energy than they save (184). Similarly, human memory systems require sufficient energy to encode information (and hence encode no more information than needed to tackle evolutionary tasks) (185, 186). Although Szilard's Paradox usefully highlights the energetic requirements of digitalization, its relevance is limited because the Earth system is not thermodynamically closed, with many orders of magnitude more incoming solar radiation than is currently appropriated by the biosphere and technosphere. On a planetary scale, the principle of maximum entropy production suggests that sufficiently complex (Earth) systems consume useful energy as quickly as possible to maximize entropy, as exemplified by heat transport between tropical and polar regions (187). Hypothetically, technological and digital systems that evolve toward greater complexity could also follow the principle of maximum entropy production and increasingly appropriate useful energy (188), potentially in competition to useful energy required for human well-being (8).

outcomes for the commons and society. The process of forming societal goals needs to be informed by a clear understanding of the current state, trends, and plausible futures of digitalization and its impacts, and mobilized by a socially equitable and participatory process to reflect diverse norms, worldviews, and value systems (179). This process includes, for example, explicit reexamination and integration of digitalization in line with the UN Sustainable Development Goals and developing a perspective for repurposing digitalization toward achieving those goals. Technically, this could translate into utilizing digitalization for realizing a high–service level, low–resource use society, drawing on demand-side options (180).

The fourth and broadest leverage point is a mindset paradigm shift away from disjointed economic, legal, natural, or cultural systems toward a synthetic consideration, as captured by the notion of the Anthropocene (14). Paradigm shifts crystallize at the level of education and human capital and may range from a novel understanding of digital citizenship (see the sidebar titled Information and Energy: A Mutual Relationship) to interpreting knowledge (including the results of applying AI on massive data sets) as a common rather than a private good. A synthetic system understanding may also enable a shift in the design of economic control instruments, such as the possibility of not only considering the control of damages (e.g., pricing externalities though the concept will remain important) but also resetting the goals of the system in alignment with planetary stability (e.g., redirecting multilevel governance toward biosphere stewardship) (181).

5. CONCLUSIONS

Digital trajectories will increasingly influence the Anthropocene. Currently, popular attention is focused on specific case studies, like the energy consumption of Bitcoin. While these are important exemplary issues, our overarching analysis suggests that the real influence on digitalization in the Anthropocene is revealed on a system level. Throughout history, ICTs and digital technologies have demonstrated the ability to increase the efficiency of processes, sometimes leading to a quantum leap in technological change, an associated opportunity for expanded control and power in time and space, and regularly associated (though not strictly necessitated) ecological disasters. Maintaining planetary stability will depend on global cooperation to restrict environmental overuse of atmospheric sinks, land, and other natural resources and to make wise use of digital technologies. Digitalization's impact on humanity will depend on the choice of computing architecture and associated collective decisions, including the design of new institutions such as data trusts. By advancing political agency, enabling more equitable societies, and reducing GHG emissions to net zero in a few decades, digitalization has the potential to positively shape the future of humanity and the only livable planet we know.

SUMMARY POINTS

1. Digitalization and its precursor, information and communication technologies, are entangled with political control and resource exploitation systems.
2. Historically, communication technologies and feedback systems were key for water management, state building, and coal-based industrialization.
3. Digital technologies and artificial intelligence directly increase energy demand, scale up resource consumption, for example via targeted advertising, and increase marginal efficiency in resource use.
4. Digitalization impacts labor markets via various channels and—under current political and economic boundary conditions—increases inequality.
5. Current applications in social media polarize societies.
6. Via inequality and polarization, digitalization and artificial intelligence render deliberate policy making and stabilization of planetary dynamics, for example climate change mitigation, more difficult.
7. Current trajectories suggest a contribution of digitalization to further planetary destabilization but—with public policy—digitalization can support planetary health without or together with equity and political agency.
8. Key leverage points redirecting digitalization toward stabilization of human and planetary systems include the control of digitalization effects with rules and negative feedback loops, generation and shaping of new digital knowledge structures, the setting of new goals that align individual interests with social and planetary stability, and associated paradigm shifts.

FUTURE ISSUES

1. Future work will need to research the history of digitalization, its role in efficiency gains, and its impact on consumption culture.
2. Researchers will aim to identify strategies to reduce the environmental impact and scaled resource consumption of digitalization.
3. Applying digital knowledge systems, such as big data approaches on the built environment, to accelerate climate change mitigation and sustainability strategies, such as low-carbon urban planning, will become an increasingly important arena for research.

4. Studying the co-evolution of digital knowledge and communication systems with equitable, deliberative and sustainable societies is a key task for interdisciplinary investigations.
5. Modeling the co-evolution of knowledge (for example, including the role of cognitive artifacts) and technology systems (for example, automobility), as shaped by digitalization, and their joined impact on the environment becomes an important area for collaborative research between humanities and (data) engineers.
6. Operationalizing leverage points of the coupled digital-human-planetary system within dynamic system models is a high-level task for researchers of the Anthropocene.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

AUTHOR CONTRIBUTIONS

F.C. conceptualized the review and wrote the first version. All authors wrote additional paragraphs and edited the manuscript. F.C. and N.M.D. provided **Figure 1**, St.K. provided **Figure 2**, F.W. and M.Z. provided **Figure 3**, N.M.D. provided **Figure 4**, and X.B. and F.C. provided **Figure 5**. S.K. synthesized **Table 3**.

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LITERATURE CITED

1. Crutzen PJ. 2006. The 'Anthropocene.' In *Earth System Science in the Anthropocene*, ed. E Ehlers, T Krafft, pp. 13–18. Berlin: Springer
2. Steffen W, Grinevald J, Crutzen P, McNeill J. 2011. The Anthropocene: conceptual and historical perspectives. *Philos. Trans. R. Soc. A* 369:842–67
3. Steffen W, Broadgate W, Deutsch L, Gaffney O, Ludwig C. 2015. The trajectory of the Anthropocene: the Great Acceleration. *Anthr. Rev.* 2:81–98
4. Syvitski J, Waters CN, Day J, Milliman JD, Summerhayes C, et al. 2020. Extraordinary human energy consumption and resultant geological impacts beginning around 1950 CE initiated the proposed Anthropocene Epoch. *Commun. Earth Environ.* 1:32
5. Nakicenovic N. 2019. *TWI2050—the world in 2050. The digital revolution and sustainable development: opportunities and challenges*. Rep., World 2050 Initiat., Laxenburg, Austria
6. Schinckus C. 2020. The good, the bad and the ugly: an overview of the sustainability of blockchain technology. *Energy Res. Soc. Sci.* 69:101614

7. WBGU (Ger. Advis. Counc. Glob. Change). 2019. *Towards our common digital future*. Flagship Rep., WBGU, Berlin. **https://www.wbgu.de/fileadmin/user_upload/wbgu/publikationen/hauptgutachten/hg2019/pdf/wbgu_hg2019_en.pdf**
8. Haff PK. 2014. Technology as a geological phenomenon: implications for human well-being. *Geol. Soc. Lond. Spec. Publ.* 395:301–9
9. Rosol C, Nelson S, Renn J. 2017. Introduction: in the machine room of the Anthropocene. *Anthr. Rev.* 4:2–8
10. Nissen HJ, Damerow P, Englund RK. 1993. *Archaic Bookkeeping: Early Writing and Techniques of Economic Administration in the Ancient Near East*. Chicago: Univ. Chicago Press
11. Carneiro RL. 1970. A theory of the origin of the state: Traditional theories of state origins are considered and rejected in favor of a new ecological hypothesis. *Science* 169:733–38
12. Scott JC. 1998. *Seeing Like a State: How Certain Schemes to Improve the Human Condition Have Failed*. New Haven, CT: Yale Univ. Press
13. Englund RK. 1991. Hard work—where will it get you? Labor management in Ur III Mesopotamia. *J. Near East. Stud.* 50:255–80
14. Renn J. 2020. *The Evolution of Knowledge: Rethinking Science for the Anthropocene*. Princeton, NJ: Princeton Univ. Press
15. Wilkinson TJ. 2013. Hydraulic landscapes and irrigation systems of Sumer. In *The Sumerian World*, ed. H Crawford, pp. 33–54. London: Routledge
16. Boudreau V. 2004. *The First Writing: Script Invention as History and Process*. Cambridge, UK: Cambridge Univ. Press
17. Dickson DB. 1987. Circumscription by anthropogenic environmental destruction: an expansion of Carneiro's (1970) *Theory of the Origin of the State*. *Am. Antiq.* 52:709–16
18. Cameron R. 1982. The industrial revolution: a misnomer. *Hist. Teach.* 15:377–84
19. Squicciarini MP, Voigtländer N. 2015. Human capital and industrialization: evidence from the Age of Enlightenment. *Q. J. Econ.* 130:1825–83
20. Mokyr J. 2002. *The Gifts of Athena: Historical Origins of the Knowledge Economy*. Princeton, NJ: Princeton Univ. Press
21. Turnbull T. 2021. Energy, history, and the humanities: against a new determinism. *Hist. Technol.* 2:247–92
22. Nef JU. 1932. *The Rise of the British Coal Industry*. 2 vol. London: Routledge
23. Albritton Jonsson F. 2012. The industrial revolution in the Anthropocene. *J. Mod. Hist.* 84:679–96
24. Malm A. 2014. *Fossil capital: the rise of steam-power in the British cotton industry, c. 1825–1848, and the roots of global warming*. PhD Thesis, Lund Univ., Lund. Swed.
25. Pomeranz K. 2000. *The Great Divergence: China, Europe, and the Making of the Modern World Economy*. Princeton, NJ: Princeton Univ. Press
26. Wrigley EA. 2013. Energy and the English industrial revolution. *Philos. Trans. R. Soc. A* 371:20110568
27. De Pleijt AM, Weisdorf JL. 2017. Human capital formation from occupations: the 'deskilling hypothesis' revisited. *Cliometrica* 11:1–30
28. de Pleijt A, Nuvolari A, Weisdorf J. 2020. Human capital formation during the first Industrial Revolution: evidence from the use of steam engines. *J. Eur. Econ. Assoc.* 18:829–89
29. Clapham JH. 1959. *An Economic History of Modern Britain*, Vol. 2. Cambridge, UK: Cambridge Univ. Press
30. Wise MN, Smith C. 1989. Work and waste: political economy and natural philosophy in nineteenth century Britain. *Hist. Sci.* 27:391–449
31. Hills RL, Pacey AJ. 1972. The measurement of power in early steam-driven textile mills. *Technol. Cult.* 13:25–43
32. Mayr O. 1971. Maxwell and the origins of cybernetics. *Isis* 62:425–44
33. Hughes TP. 1993. *Networks of Power: Electrification in Western Society, 1880–1930*. Baltimore, MD: Johns Hopkins Univ. Press
34. Mindell DA. 2004. *Between Human and Machine: Feedback, Control, and Computing Before Cybernetics*. Baltimore, MD: Johns Hopkins Univ. Press
35. Gooday G. 2004. Profit and prophecy: electricity in the late-Victorian periodical. In *Science in the Nineteenth-Century Periodical*, ed. GN Cantor, pp. 238–54. New York: Cambridge Univ. Press

36. Jevons HS. 1931. The second industrial revolution. *Econ. J.* 41:1–18
37. Zimmermann EW. 1933. *World Resources and Industries*. New York: Harper
38. Kander A, Malanima P, Warde P. 2014. *Power to the People: Energy in Europe over the Last Five Centuries*. Princeton, NJ: Princeton Univ. Press
39. Haberl H, Wiedenhofer D, Virág D, Kalt G, Plank B, et al. 2020. A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions. Part II: Synthesizing the insights. *Environ. Res. Lett.* 15:065003
40. Brynjolfsson E, Rock D, Syverson C. 2021. The productivity J-curve: how intangibles complement general purpose technologies. *Am. Econ. J. Macroecon.* 13(1):333–72
41. Bresnahan T. 2010. General purpose technologies. In *Handbook of the Economics of Innovation*, Vol. 2, ed. BH Hall, N Rosenberg, pp. 761–91. Amsterdam: North-Holland
42. Halpern O. 2015. *Beautiful Data*. Durham, NC: Duke Univ. Press
43. Kline RR. 2015. *The Cybernetics Moment: Or Why We Call Our Age the Information Age*. Baltimore, MD: Johns Hopkins Univ. Press
44. Abbate J. 1999. *Inventing the Internet*. Cambridge, MA: MIT Press
45. Rosol C, Steininger B, Renn J, Schlögl R. 2018. On the age of computation in the epoch of humankind. *Nat. Portf.* 563:1–5
46. Zalasiewicz J, Waters CN, Williams M, Barnosky AD, Cearreta A, et al. 2015. When did the Anthropocene begin? A mid-twentieth century boundary level is stratigraphically optimal. *Quat. Int.* 383:196–203
47. Zalasiewicz J, Waters CN, Summerhayes CP, Wolfe AP, Barnosky AD, et al. 2017. The Working Group on the Anthropocene: summary of evidence and interim recommendations. *Anthropocene* 19:55–60
48. Rosol C, Steininger B, Renn J, Schlögl R. 2018. *Die digitale Transformation und die Geo-Anthropologie*. White Pap., Max-Planck-Gesellschaft, Novemb. 30. **https://www.mpg.de/12545963/geo-anthropologie-digitale-transformation** (in German)
49. Windarto AP, Dewi LS, Hartama D. 2017. Implementation of artificial intelligence in predicting the value of Indonesian oil and gas exports with BP algorithm. *Int. J. Recent Trends Eng. Res.* 3(10):1–12
50. Krausmann F, Wiedenhofer D, Lauk C, Haas W, Tanikawa H, et al. 2017. Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. *PNAS* 114:1880–85
51. Cooper AH, Brown TJ, Price SJ, Ford JR, Waters CN. 2018. Humans are the most significant global geomorphological driving force of the 21st century. *Anthr. Rev.* 5:222–29
52. Matthess M, Kunkel S. 2020. Structural change and digitalization in developing countries: conceptually linking the two transformations. *Technol. Soc.* 63:101428
53. Bardhan A, Kroll CA. 2003. *The new wave of outsourcing*. Work. Pap., Univ. Calif., Berkeley. **https:/doi.org/10.2139/ssrn.985741**
54. Jensen PH, Stonecash RE. 2005. Incentives and the efficiency of public sector–outsourcing contracts. *J. Econ. Surv.* 19:767–87
55. Graham M, Hjorth I, Lehdonvirta V. 2017. Digital labour and development: impacts of global digital labour platforms and the gig economy on worker livelihoods. *Transf. Eur. Rev. Labour Res.* 23:135–62
56. Banga K, te Velde DW. 2018. *Digitalisation and the future of manufacturing in Africa*. Res. Rep., ODI, London
57. Michaels G, Natraj A, Van Reenen J. 2014. Has ICT polarized skill demand? Evidence from eleven countries over twenty-five years. *Rev. Econ. Stat.* 96:60–77
58. Acemoglu D, Restrepo P. 2019. Automation and new tasks: how technology displaces and reinstates labor. *J. Econ. Perspect.* 33:3–30
59. Barbieri L, Mussida C, Piva M, Vivarelli M. 2019. *Testing the employment impact of automation, robots and AI: a survey and some methodological issues*. IZA Discuss. Pap. 12612, Inst. Labor Econ., Bonn, Ger.
60. Kerr S, Maczulskij T, Maliranta M. 2020. Within and between firm trends in job polarization: the roles of globalization and technology. *J. Econ. Geogr.* 20:1003–39
61. Autor D. 2019. *Work of the past, work of the future*. NBER Work. Pap. 25588
62. Acemoglu D, Autor D. 2011. Skills, tasks and technologies: implications for employment and earnings. In *Handbook of Labor Economics*, ed. D Card, O Ashenfelter, pp. 1043–171. Amsterdam: Elsevier

63. Acemoglu D, Restrepo P. 2020. Robots and jobs: evidence from US labor markets. *J. Political Econ.* 128:2188–244
64. Chiacchio F, Petropoulos G, Pichler D. 2018. *The impact of industrial robots on EU employment and wages: a local labour market approach*. Work. Pap., Breughel, Josse-ten-Noode, Belg.
65. Dauth W, Findeisen S, Suedekum J, Woessner N. 2017. *German robots—the impact of industrial robots on workers*. IAB Discuss. Pap. 30/2017, Inst. Employ. Res., Nuremberg, Ger.
66. Dottori D. 2021. Robots and employment: evidence from Italy. *Econ. Politica* 38:739–95
67. Pohl J, Höfner A, Albers E, Rohde F. 2021. Design options for long-lasting, efficient and open hardware and software. *Ökol. Wirtsch. Fachz.* 36:20–24
68. Hischier R, Coroama VC, Schien D, Ahmadi Achachlouei M. 2015. Grey energy and environmental impacts of ICT hardware. In *ICT Innovations for Sustainability*, ed. LM Hilty, B Aebischer, pp. 171–89. Cham, Switz.: Springer Int.
69. Nkulu CBL, Casas L, Haufroid V, De Putter T, Saenen ND, et al. 2018. Sustainability of artisanal mining of cobalt in DR Congo. *Nat. Sustain.* 1:495–504
70. Pilgrim H, Reckordt M, Groneweg M. 2017. *Ressourcenfluch 4.0: die sozialen und ökologischen Auswirkungen von Industrie 4.0 auf den Rohstoffsektor*. Rep., PowerShift, Berlin
71. Awasthi AK, Li J, Koh L, Ogunseitan OA. 2019. Circular economy and electronic waste. *Nat. Electron.* 2:86–89
72. Evermann A. 2018. *Am anderen Ende der Lieferkette: Was tun IT-Hersteller für einen verantwortungsvollen Bezug von Rohstoffen?* Rep., WEED (Weltwirtschaft, Ökologie & Entwicklung e.V.), Berlin. **https://www2.weed-online.org/uploads/weed_studie_rohstoffe_web.pdf**
73. Max Planck Found. 2016. *Human rights risks in mining: a baseline study*. Rep., Bund. Geowiss. Rohst., Berlin. **https://www.bgr.bund.de/DE/Themen/Zusammenarbeit/TechnZusammenarbeit/Downloads/human_rights_risks_in_mining.pdf?__blob=publicationFile&v=2**
74. Eftimie A, Heller K, Strongman J, Hinton J, Lahiri-Dutt K, Mutemeri N. 2012. *Gender dimensions of artisanal and small-scale mining: a rapid assessment toolkit*. Rep., World Bank, Washington, DC. **https://openknowledge.worldbank.org/handle/10986/2731**
75. Coderre-Proulx M, Campbell B, Mandé I. 2016. *International migrant workers in the mining sector*. Rep., Int. Labour Off., Geneva. **https://labordoc.ilo.org/discovery/delivery/41ILO_INST:41ILO_V1/1244629950002676**
76. Bahadur A, Leifker M, Lincoln S. 2018. *Edles Metall—unwürdiger Abbau. Platin aus Südafrika und die Verantwortung deutscher Unternehmen*. Anal. 75, Brot für die Welt, Berlin
77. Sovacool BK. 2021. When subterranean slavery supports sustainability transitions? Power, patriarchy, and child labor in artisanal Congolese cobalt mining. *Extr. Ind. Soc.* 8:271–93
78. Zimm C. 2019. Methodological issues in measuring international inequality in technology ownership and infrastructure service use. *Dev. Stud. Res.* 6:92–105
79. ITU (Int. Telecommun. Union). 2020. *Measuring digital development: facts and figures 2020*. Fact Sheet, ITU, Geneva. **https://www.itu.int/en/ITU-D/Statistics/Documents/facts/FactsFigures2020.pdf**
80. Cruz-Cárdenas J, Zabelina E, Guadalupe-Lanas J, Palacio-Fierro A, Ramos-Galarza C. 2021. COVID-19, consumer behavior, technology, and society: a literature review and bibliometric analysis. *Technol. Forecast. Soc. Change* 173:121179
81. Mayer-Schonberger V, Ramge T. 2019. *Reinventing Capitalism in the Age of Big Data*. London: Murray
82. Kryvasheyeu Y, Chen H, Obradovich N, Moro E, Van Hentenryck P, et al. 2016. Rapid assessment of disaster damage using social media activity. *Sci. Adv.* 2:e1500779
83. Baylis K, Paulson ND. 2011. Potential for carbon offsets from anaerobic digesters in livestock production. *Anim. Feed Sci. Technol.* 166–67:446–56
84. Ilieva RT, McPhearson T. 2018. Social-media data for urban sustainability. *Nat. Sustain.* 1:553–65
85. Creutzig F, Lohrey S, Bai X, Baklanov A, Dawson R, et al. 2019. Upscaling urban data science for global climate solutions. *Glob. Sustain.* 2:e2
86. Nonnecke B, Carlton C. 2022. EU and US legislation seek to open up digital platform data. *Science* 375:610–12
87. Koski H, Pantzar M. 2021. *Data markets in making: the role of technology giants*. ETLA Work. Pap. 72, Res. Inst. Finn. Econ., Helsinki

88. Zuboff S. 2019. Surveillance capitalism. *Esprit* 5:63–77
89. Kosinski M, Stillwell D, Graepel T. 2013. Private traits and attributes are predictable from digital records of human behavior. *PNAS* 110:5802–5
90. Youyou W, Kosinski M, Stillwell D. 2015. Computer-based personality judgments are more accurate than those made by humans. *PNAS* 112:1036–40
91. Aho B, Duffield R. 2020. Beyond surveillance capitalism: privacy, regulation and big data in Europe and China. *Econ. Soc.* 49:187–212
92. Fukuyama F, Richman B, Goel A. 2021. How to save democracy from technology: ending Big Tech's information monopoly. *Foreign Aff.* 100:98
93. Zollo F, Quattrociocchi W. 2018. Misinformation spreading on Facebook. In *Complex Spreading Phenomena in Social Systems: Influence and Contagion in Real-World Social Networks*, ed. S Lehmann, Y-Y Ahn, pp. 177–96. Cham, Switz.: Springer Int.
94. Persily N. 2017. The 2016 U.S. election: Can democracy survive the Internet? *J. Democr.* 28:63–76
95. Karlsen R, Aalberg T. 2021. Social media and trust in news: an experimental study of the effect of Facebook on news story credibility. *Digit. Journal.* **https://doi.org/10.1080/21670811.2021.1945938**
96. Berkhout F, Hertin J. 2004. De-materialising and re-materialising: digital technologies and the environment. *Futures* 36:903–20
97. Horner NC, Shehabi A, Azevedo IL. 2016. Known unknowns: indirect energy effects of information and communication technology. *Environ. Res. Lett.* 11:103001
98. Koomey JG, Matthews HS, Williams E. 2013. Smart everything: Will intelligent systems reduce resource use? *Annu. Rev. Environ. Resour.* 38:311–43
99. Hilty LM, Aebischer B. 2015. ICT for sustainability: an emerging research field. In *ICT Innovations for Sustainability*, ed. LM Hilty, B Aebischer, pp. 3–36. Cham, Switz.: Springer Int.
100. Malmodin J, Bergmark P, Matinfar S. 2018. A high-level estimate of the material footprints of the ICT and the E&M sector. In *Proceedings of the 5th International Conference on Information and Communication Technology for Sustainability* (*ICT4S*), pp. 168–86. Manchester, UK: EasyChair
101. Forti V, Balde CP, Kuehr R, Bel G. 2020. *The Global E-Waste Monitor 2020: Quantities, Flows, and the Circular Economy Potential*. Geneva: U. N. Univ.
102. Lange S, Pohl J, Santarius T. 2020. Digitalization and energy consumption: Does ICT reduce energy demand? *Ecol. Econ.* 176:106760
103. Dauvergne P. 2022. Is artificial intelligence greening global supply chains? Exposing the political economy of environmental costs. *Rev. Int. Political Econ.* 29:696–718
104. Kaack LH, Donti PL, Strubell E, Kamiya G, Creutzig F, Rolnick D. 2022. Aligning artificial intelligence with climate change mitigation. *Nat. Clim. Change* 12:518–27
105. Jones N. 2018. How to stop data centres from gobbling up the world's electricity. *Nature* 561:163–67
106. Strubell E, Ganesh A, McCallum A. 2019. Energy and policy considerations for deep learning in NLP. arXiv:1906.02243 [cs]
107. Masanet E, Shehabi A, Lei N, Smith S, Koomey J. 2020. Recalibrating global data center energy-use estimates. *Science* 367:984–86
108. Huang P, Copertaro B, Zhang X, Shen J, Löfgren I, et al. 2020. A review of data centers as prosumers in district energy systems: renewable energy integration and waste heat reuse for district heating. *Appl. Energy* 258:114109
109. Google. 2020. *Realizing a carbon-free future: Google's third decade of climate action*. Rep., Google, Mountain View, CA. **https://clim8.com/wp-content/uploads/2020/11/carbon-free-by-203012.pdf**
110. Varro L, Kamiya G. 2021. *5 ways Big Tech could have big impacts on clean energy transitions*. Commentary, Int. Energy Agency, Paris. **https://www.iea.org/commentaries/5-ways-big-tech-could-have-big-impacts-on-clean-energy-transitions**
111. Grubler A, Wilson C, Bento N, Boza-Kiss B, Krey V, et al. 2018. A low energy demand scenario for meeting the 1.5°C target and sustainable development goals without negative emission technologies. *Nat. Energy* 3:515–27
112. Vinuesa R, Azizpour H, Lente I, Balaam M, Dignum V, et al. 2020. The role of artificial intelligence in achieving the Sustainable Development Goals. *Nat. Commun.* 11:233

113. Rolnick D, Donti PL, Kaack LH, Kochanski K, Lacoste A, et al. 2021. Tackling climate change with machine learning. *ACM Comput. Surv.* 55:42

114. Creutzig F, Franzen M, Moeckel R, Heinrichs D, Nieland S, et al. 2019. Leveraging digitalization for sustainability in urban transport. *Glob. Sustain.* 2:e14

115. Edwards PN. 2017. Knowledge infrastructures for the Anthropocene. *Anthr. Rev.* 4:34–43

116. Reichstein M, Camps-Valls G, Stevens B, Jung M, Denzler J, et al. 2019. Deep learning and process understanding for data-driven Earth system science. *Nature* 566:195–204

117. Kruitwagen L, Story KT, Friedrich J, Byers L, Skillman S, Hepburn C. 2021. A global inventory of photovoltaic solar energy generating units. *Nature* 598:604–10

118. Masson-Delmotte V, Zhai P, Pörtner H-O, Roberts D, Skea J, et al., eds. 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*. Rep., IPCC, Geneva

119. Nawaz A, Hafeez G, Khan I, Jan KU, Li H, Khan SA, et al. 2020. An intelligent integrated approach for efficient demand side management with forecaster and advanced metering infrastructure frameworks in smart grid. *IEEE Access* 8:132551–81

120. Buckley P. 2020. Prices, information and nudges for residential electricity conservation: a meta-analysis. *Ecol. Econ.* 172:106635

121. Khanna TM, Baiocchi G, Callaghan M, Creutzig F, Guias H, et al. 2021. A multi-country meta-analysis on the role of behavioural change in reducing energy consumption and CO_2 emissions in residential buildings. *Nat. Energy* 6:925–32

122. Zeng W, Miwa T, Morikawa T. 2017. Application of the support vector machine and heuristic k-shortest path algorithm to determine the most eco-friendly path with a travel time constraint. *Transport. Res. D* 57:458–73

123. Cazzola P, Crist P. 2020. *Good to go? Assessing the environmental performance of new mobility*. Rep., Int. Transp. Forum, Paris. **https://www.itf-oecd.org/good-go-assessing-environmental-performance-new-mobility**

124. Creutzig F. 2021. *Making smart mobility sustainable: how to leverage the potential of smart and shared mobility to mitigate climate change*. Policy Pap., Isr. Public Policy Inst., Tel Aviv

125. Milojevic-Dupont N, Creutzig F. 2020. Machine learning for geographically differentiated climate change mitigation in urban areas. *Sustain. Cities Soc.* 64:102526

126. Zawieska J, Pieriegud J. 2018. Smart city as a tool for sustainable mobility and transport decarbonisation. *Transp. Policy* 63:39–50

127. Deichmann U, Goyal A, Mishra D. 2016. Will digital technologies transform agriculture in developing countries? *Agric. Econ.* 47:21–33

128. Chlingaryan A, Sukkarieh S, Whelan B. 2018. Machine learning approaches for crop yield prediction and nitrogen status estimation in precision agriculture: a review. *Comput. Electron. Agric.* 151:61–69

129. World Bank. 2019. *Future of food: harnessing digital technologies to improve food system outcomes*. Rep., World Bank, Washington, DC

130. Parida V, Sjödin D, Reim W. 2019. Reviewing literature on digitalization, business model innovation, and sustainable industry: past achievements and future promises. *Sustainability* 11:391

131. Aghaei J, Alizadeh M-I. 2013. Demand response in smart electricity grids equipped with renewable energy sources: a review. *Renew. Sustain. Energy Rev.* 18:64–72

132. Voyant C, Notton G, Kalogirou S, Nivet ML, Paoli C, et al. 2017. Machine learning methods for solar radiation forecasting: a review. *Renew. Energy* 105:569–82

133. Vázquez-Canteli JR, Nagy Z. 2019. Reinforcement learning for demand response: a review of algorithms and modeling techniques. *Appl. Energy* 235:1072–89

134. Andrae A, Edler T. 2015. On global electricity usage of communication technology: trends to 2030. *Challenges* 6:117–57

135. Rikap C. 2020. Amazon: a story of accumulation through intellectual rentiership and predation. *Compet. Change.* **https://doi.org/10.1177/1024529420932418**

136. Deetman S, Pauliuk S, van Vuuren DP, van der Voet E, Tukker A. 2018. Scenarios for demand growth of metals in electricity generation technologies, cars, and electronic appliances. *Environ. Sci. Technol.* 52:4950–59
137. Pitron G. 2018. *La guerre des métaux rares*. Paris: LLL
138. Taj F, Klein MCA, van Halteren A. 2019. Digital health behavior change technology: bibliometric and scoping review of two decades of research. *JMIR mHealth uHealth* 7:e13311
139. Calvão F, Archer M. 2021. Digital extraction: blockchain traceability in mineral supply chains. *Political Geogr.* 87:102381
140. Kunkel S, Tyfield D. 2021. Digitalisation, sustainable industrialisation and digital rebound—asking the right questions for a strategic research agenda. *Energy Res. Soc. Sci.* 82:102295
141. Mironkina A, Kharitonov S, Kuchumov A, Belokopytov A. 2020. Digital technologies for efficient farming. *IOP Conf. Ser. Earth Environ. Sci.* 578:012017
142. Wolniak R, Saniuk S, Grabowska S, Gajdzik B. 2020. Identification of energy efficiency trends in the context of the development of Industry 4.0 using the Polish steel sector as an example. *Energies* 13:2867
143. Kleidon A. 2022. Empowering the Earth system by technology: using thermodynamics of the Earth system to illustrate a possible sustainable future of the planet. In *Strategies for Sustainability of the Earth System*, ed. PA Wilderer, M Grambow, M Molls, K Oexle, pp. 433–44. Berlin: Springer
144. Michalek G, Meran G, Schwarze R, Yildiz Ö. 2015. Nudging as a new "soft" tool in environmental policy—an analysis based on insights from cognitive and social psychology. In *RECAP15: Re-Thinking the Efficacy of International Climate Change Agreements Post COP15*, Discuss. Pap. 20. Frankfurt, Ger.: Eur. Univ. Viadrina
145. Clarke R. 2019. Risks inherent in the digital surveillance economy: a research agenda. *J. Inf. Technol.* 34:59–80
146. Di Silvestre ML, Favuzza S, Riva Sanseverino E, Zizzo G. 2018. How decarbonization, digitalization and decentralization are changing key power infrastructures. *Renew. Sustain. Energy Rev.* 93:483–98
147. Schmück K, Sturm M, Gassmann O. 2021. Decentralized platform ecosystems for data and digital trust in industrial environments. In *Connected Business: Create Value in a Networked Economy*, ed. O Gassmann, F Ferrandina, pp. 127–36. Cham, Switz.: Springer Int.
148. Deseriis M. 2021. Rethinking the digital democratic affordance and its impact on political representation: toward a new framework. *New Media Soc.* 23:2452–73
149. Luers A. 2020. Leveraging digital disruptions for a climate-safe and equitable world: the D^2S agenda. *IEEE Technol. Soc. Mag.* 39:18–31
150. Strefler J, Kriegler E, Bauer N, Luderer G, Pietzcker RC, et al. 2021. Alternative carbon price trajectories can avoid excessive carbon removal. *Nat. Commun.* 12:2264
151. Mattauch L, Creutzig F, aus dem Moore N, Franks M, Funke F, et al. 2019. *Antworten auf zentrale Fragen zur Einführung von* CO_2 *Preisen*. Rep., Sci. Future, Clim. Change Cent., Vienna
152. Amazon. 2021. *Faster and further, together*. Sustain. Rep., Amazon, Seattle, WA. **https://sustainability.aboutamazon.com/pdfBuilderDownload?name=amazon-sustainability-2020-report**
153. Truby J, Brown RD, Dahdal A, Ibrahim I. 2022. Blockchain, climate damage, and death: policy interventions to reduce the carbon emissions, mortality, and net-zero implications of non-fungible tokens and Bitcoin. *Energy Res. Soc. Sci.* 88:102499
154. Rockström J, Beringer T, Hole D, Creutzer F. 2021. We need biosphere stewardship that protects carbon sinks and builds resilience. *PNAS* 118:e2115218118
155. World Econ. Forum. 2019. *A new circular vision for electronics: time for a global reboot.* Rep., World Econ. Forum, Geneva. **https://www3.weforum.org/docs/WEF_A_New_Circular_Vision_for_Electronics.pdf**
156. R. Soc. 2020. *Digital technology and the planet: harnessing computing to achieve net zero*. Rep., R. Soc., London
157. Bai X, Nagendra H, Shi P, Liu H. 2020. Cities: build networks and share plans to emerge stronger from COVID-19. *Nature* 584:517–20
158. Preist C, Schien D, Shabajee P. 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*, Pap. 397. New York: ACM

159. Shaviro D. 2019. *Digital services taxes and the broader shift from determining the source of income to taxing location-specific rents*. Law Econ. Res. Pap. 19-36, NYU, New York
160. Soergel B, Kriegler E, Bodirsky BL, Bauer N, Leimbach M, Popp A. 2021. Combining ambitious climate policies with efforts to eradicate poverty. *Nat. Commun.* 12:2342
161. Creutzig F. 2019. The mitigation trinity: coordinating policies to escalate climate mitigation. *One Earth* 1:76–85
162. Kornek U, Edenhofer O. 2020. The strategic dimension of financing global public goods. *Eur. Econ. Rev.* 127:103423
163. POSMO Coop. 2021. The data cooperative: a new business model for the digital economy. *Medium*, Oct. 31
164. Creutzig F. 2021. From smart city to digital urban commons: institutional considerations for governing shared mobility data. *Environ. Res. Infrastruct. Sustain.* 1:025004
165. Adeodato R, Pournouri S. 2020. Secure implementation of e-governance: a case study about Estonia. In *Cyber Defence in the Age of AI, Smart Societies and Augmented Humanity*, ed. H Jahankhani, S Kendzierskyj, N Chelvachandran, J Ibarra, pp. 397–429. Cham, Switz.: Springer Int.
166. Afonso JR. 2017. Estonia, the digital republic. *New Yorker*, Dec. 25
167. Bharosa N, Lips S, Draheim D. 2020. Making e-government work: learning from the Netherlands and Estonia. In *Electronic Participation*, ed. S Hofmann, C Csáki, N Edelmann, T Lampoltshammer, U Melin, et al., pp. 41–53. Berlin: Springer
168. Eur. Comm. 2020. *A new Circular Economy Action Plan for a cleaner and more competitive Europe*. Position Pap., Eur. Comm., Brussels/Luxembourg
169. Wieser H, Tröger N. 2018. Exploring the inner loops of the circular economy: replacement, repair, and reuse of mobile phones in Austria. *J. Clean. Prod.* 172:3042–55
170. Tzani D, Stavrakas V, Santini M, Thomas S, Rosenow J, Flamos A. 2022. Pioneering a performance-based future for energy efficiency: lessons learnt from a comparative review analysis of pay-for-performance programmes. *Renew. Sustain. Energy Rev.* 158:112162
171. Kazmi H, Munné-Collado Í, Mehmood F, Syed TA, Driesen J. 2021. Towards data-driven energy communities: a review of open-source datasets, models and tools. *Renew. Sustain. Energy Rev.* 148:111290
172. Brockway PE, Sorrell S, Semieniuk G, Heun MK, Court V. 2021. Energy efficiency and economy-wide rebound effects: a review of the evidence and its implications. *Renew. Sustain. Energy Rev.* 141:110781
173. Ruiz D, San Miguel G, Rojo J, Teriús-Padrón JG, Gaeta E, et al. 2022. Life cycle inventory and carbon footprint assessment of wireless ICT networks for six demographic areas. *Resour. Conserv. Recycl.* 176:105951
174. Eur. Comm. 2018. *Time to establish a modern, fair and efficient taxation standard for the digital economy*. Commun. 146, Eur. Comm., Brussels/Luxembourg. **https://eur-lex.europa.eu/resource.html?uri=cellar:2bafa0d9-2dde-11e8-b5fe-01aa75ed71a1.0017.02/DOC_1&format=PDF**
175. Prüfer J. 2020. *Competition policy and data sharing on data-driven markets*. Friedrich-Ebert-Stiftung Proj., Tilburg Univ., Tilburg, Neth.
176. Jackman JA, Gentile DA, Cho N-J, Park Y. 2021. Addressing the digital skills gap for future education. *Nat. Hum. Behav.* 5:542–45
177. Meadows DH. 1999. *Leverage points: places to intervene in a system*. Rep., Sustain. Inst., Hartland, VT. **https://donellameadows.org/wp-content/userfiles/Leverage_Points.pdf**
178. Potters JI, Termeer C, Opdam PFM, eds. 2016. *Organising Sustainability in the Digital Age: Results of the Research Programme Informational Governance for Sustainability 2012–2016*. Wageningen, Neth.: Wageningen Univ.
179. Bai X, van der Leeuw S, O'Brien K, Berkhout F, Fiermann F, et al. 2016. Plausible and desirable futures in the Anthropocene: a new research agenda. *Glob. Environ. Change* 39:351–62
180. Creutzig F, Niamir L, Bai X, Callaghan M, Cullen J, et al. 2021. Demand-side solutions to climate change mitigation consistent with high levels of well-being. *Nat. Clim. Change* 12:36–46
181. Creutzig F. 2020. Limits to liberalism: considerations for the Anthropocene. *Ecol. Econ.* 177:106763
182. Szilard L. 1929. Über die Entropieverminderung in einem thermodynamischen System bei Eingriffen intelligenter Wesen. *Z. Phys.* 53:840–56

183. Wiener N. 1950. Cybernetics. *Bull. Am. Acad. Arts Sci.* 3:2–4
184. Jauch JM, Báron JG. 1990. Entropy, information and Szilard's Paradox. In *Maxwell's Demon: Entropy, Information, Computing*, ed. HS Leff, AR Rex, pp. 160–72. Princeton, NJ: Princeton Univ. Press
185. Creutzig F. 2008. *Sufficient encoding of dynamical systems*. PhD Thesis, Humboldt Univ., Berlin
186. Tishby N, Pereira FC, Bialek W. 2000. The information bottleneck method. arXiv:physics/0004057
187. Kleidon A, Lorenz R. 2005. Entropy production by Earth system processes. In *Non-Equilibrium Thermodynamics and the Production of Entropy*, ed. A Kleidon, RD Lorenz, pp. 1–20. Berlin: Springer
188. Haff PK. 2014. Maximum entropy production by technology. In *Beyond the Second Law*, ed. RC Dewar, CH Lineweaver, RK Nguyen, K Regenauer-Lieb, pp. 397–414. Berlin: Springer

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