The Digital Revolution and Sustainable Development: Opportunities and Challenges

Report prepared by
The World in 2050 initiative

International Institute for Applied Systems Analysis
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Foreword

The Digital Revolution, including technologies such as virtual and augmented reality, additive manufacturing or 3D-printing, (general purpose) artificial intelligence, or the Internet of Things, has entered the public discourse in many countries. Looking back, it is almost impossible to believe that digitalization is barely featured in the 2030 Agenda or the Paris Agreement. It is increasingly clear that digital changes, we refer to them as the Digital Revolution, are becoming a key driving force in societal transformation. The transformation towards sustainability for all must be harmonized with the threats, opportunities and dynamics of the Digital Revolution, the goals of the 2030 Agenda and the Paris Agreement. At the same time, the digital transformation will radically alter all dimensions of global societies and economies and will therefore change the interpretation of the sustainability paradigm itself. Digitalization is not only an 'instrument' to resolve sustainability challenges, it is also fundamental as a driver of disruptive change.

This report that focuses on the Digital Revolution is the second one by The World in 2050 (TWI2050) that was established by the International Institute for Applied Systems Analysis (IIASA) and other partners to provide scientific foundations for the 2030 Agenda. This report is based on the voluntary and collaborative effort of 45 authors and contributors from about 20 institutions, and some 100 independent experts from academia, business, government, intergovernmental and non-governmental organizations from all the regions of the world, who met four times at IIASA to develop science-based strategies and pathways toward achieving the Sustainable Development Goals (SDGs). Presentations of the TWI2050 approach and work have been made at many international meetings such as the United Nations Science, Technology and Innovation Forums and the United Nations High-level Political Forums.

In 2018, the first report by TWI2050 on *Transformations to Achieve the Sustainable Development Goals* identified Six Exemplary Transformations needed to achieve the SDGs and long-term sustainability to 2050 and beyond: i) Human Capacity & Demography; ii) Consumption & Production; iii) Decarbonization & Energy, iv) Food, Biosphere & Water; v) Smart Cities and vi) Digital Revolution.

The focus of this report is the Sixth Transformation, The Digital Revolution. Although it is arguably the single greatest enabler of sustainable development, it has, in the past, helped create many negative externalities like transgression of planetary boundaries. Progress on the SDGs will be facilitated if we can build and implement detailed science, technology and innovation (STI) roadmaps at all levels that range from local to global. STI is a forceful driver of change connected to all 17 SDGs. The Digital Revolution provides entirely new and enhanced capacities and thus serves as a major force in shaping both the systemic context of transformative change and future solutions; at the same time it potentially carries strong societal disruptive power if not handled with caution, care, and innovativeness.

This report assesses all the positive potential benefits digitalization brings to sustainable development for all. It also highlights the potential negative impacts and challenges going forward, particularly for those impacted by the 'digital divide' that excludes primarily people left behind during the Industrial Revolution like the billion that go hungry every night and the billion who do not have access to electricity. The report outlines the necessary preconditions for a successful digital transformation, including prosperity, social inclusion, environmental sustainability and good governance. Importantly it outlines some of the dramatic social implications associated with an increasingly digital future. It also covers a topic that so far has not been sufficiently dealt with in the cross-over discussions between sustainability and the Digital Revolution, that is, the considerations about related governance aspects.

Completion of this report has involved voluntary and sustained contributions from many colleagues around the world. Special thanks and gratitude go to all contributing institutions that provided personal and institutional support throughout. We are especially grateful for the contribution and support of the IIASA team that has provided substantial in-kind support and vision needed to conduct an initiative of this magnitude. Special thanks go to my IIASA colleagues Caroline Zimm and Pat Wagner for coordinating and managing TWI2050, to all authors and contributors without whose knowledge and dedication this report would not have been possible.

The publication of this report in July 2019 and its launch during the United Nations High-level Political Forum is timely. TWI2050 outlines nine key considerations on the linkages between the digital and sustainability revolutions – both positive and negative – and the critical issues that need to be addressed to maximize the opportunities and minimize the risks of digitalization to a sustainable future. It is my belief that this report will provide policy and decision makers around the world with invaluable new knowledge to inform action and commitment towards achieving the SDGs in a new era. I hope it will be a roadmap toward a sustainable future in the Digital Anthropocene and will divert from the alternatives that transcend the planetary boundaries and leave billions behind.

Nebojsa Nakicenovic
TWI2050 Executive Director

Table of Contents

> “It seems probable that once the machine thinking method had started, it would not take long to outstrip our feeble powers. They would be able to converse with each other to sharpen their wits. At some stage therefore, we should have to expect the machines to take control.”
>
> *Alan Turing during a lecture on 15 May 1951 broadcast by the BBC*

Key Considerations: Digitalization and Sustainability in the Anthropocene

The predicament of humankind is to achieve a sustainable future for all within a safe and just operating space of a stable Earth system. There is significant inequality between and within societies, with billions left behind and overwhelming evidence of rising global risks due to ever-increasing human pressures on the planet. Ensuring future sustainability for all will require socioeconomic development that improves human wellbeing while preserving the resilience of the Earth’s system within planetary boundaries (Rockström et al., 2009; Steffen et al., 2015; TWI2050, 2018).

In 2015, the United Nations adopted the *2030 Agenda for Sustainable Development* (UN, 2015a), which provides an aspirational narrative and an actionable agenda to be achieved by 2030. The Agenda includes 17 Sustainable Development Goals (SDGs) and 169 targets for realizing the desired future for human development. It specifies far-reaching, time-bound, and often quantified objectives based on a comprehensive consultation among nations and civil society. For the first time, a world development agenda has been adopted that integrates ambitious goals for inclusive social and economic development for all with the parallel aim of achieving global environmental targets for land, oceans, freshwater, biodiversity, and climate, and, thereby, the protection of the global commons (Nakicenovic et al., 2016). The Agenda essentially presents a roadmap for redefining sustainable development as a people and planet agenda – a prosperous and fair world within planetary boundaries. Together with the 2015 Paris Agreement (UNFCCC, 2015), which commits all signatories to a long-term target of keeping global warming to “well below 2°C” and if possible below 1.5°C above pre-industrial levels, as well as the 2015 Addis Ababa Action Agenda (UN, 2015b), the 2030 Agenda recognizes the necessity of attaining inclusive and fair social, economic, and technological development with adequate finance within the safe operating space of a stable and resilient climate and other Earth systems.

The Digital Revolution, including virtual and augmented reality (virtual reality and AR), additive manufacturing (AM), (general purpose) artificial intelligence (AI), deep learning, robotics, big data, Internet of Things (IoT), and automated decision-making systems, has entered the public discourse in many countries. Looking back, it is almost impossible to believe that digitalization is barely featured in the 2030 Agenda[1] or the Paris Agreement. It is increasingly clear that digital changes are becoming a key driving force in societal transformation (Domingos, 2015; Schwab, 2016; Tegmark, 2017; Craglia et al, 2018). The transformation toward sustainability must be harmonized with the threats, opportunities, and dynamics of the Digital Revolution, and the goals of the 2030 Agenda and the Paris Agreement (WBGU, 2018; Villani, 2018; TWI2050, 2018). At the same time, the digital transformation will radically alter all dimensions of global societies and economies, and it will, therefore, change the interpretation of the sustainability paradigm itself. Digitalization is not only an “instrument” for resolving sustainability challenges, it is also a fundamental driver of disruptive, multiscalar change. The Digital Age can be characterized by three major dynamics, as illustrated in Figure 1.

1 While some individual technologies, foremost telecommunication technologies (e.g., mobile phones or the Internet) are mentioned within the SDGs, the overall impact of digitalization is not covered, except for one reference to the digital divide in para. 15 (UN, 2015): “The spread of information and communications technology and global interconnectedness has great potential to accelerate human progress, to bridge the digital divide and to develop knowledge societies, as does scientific and technological innovation across areas as diverse as medicine and energy.”

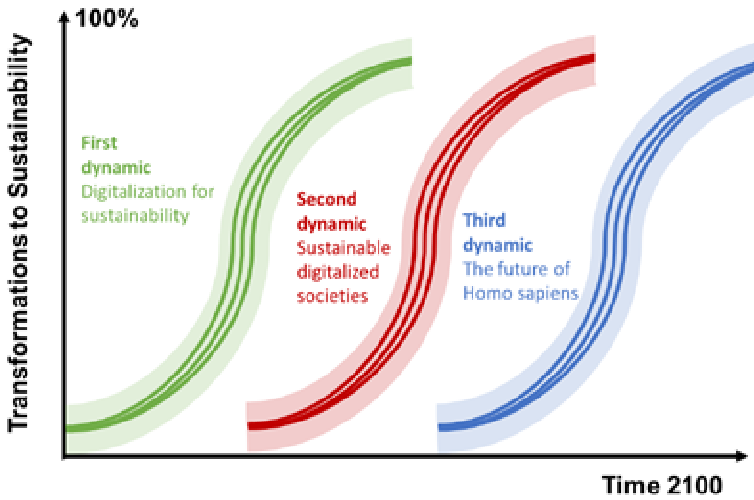

Figure 1. Three possible dynamics of the Digital Age. The chart shows the positive case of the dynamics being successfully diffused through goals and governance. All three are already emerging in parallel, albeit with different levels of intensity, so there is no strict chronological sequence involved. Each dynamic consists of multiple pathways that follow different technology trajectories. The name given to each dynamic reflects the priorities for action required in each case. For illustrative purposes, we show a simplified version that does not cover all emerging technology clusters and possible pathways. Source: Adapted from WBGU (2019).

Here we outline nine key considerations on the links – both positive and negative – between the digital and sustainability revolutions, and the critical issues that need to be addressed to maximize the opportunities and minimize the risks of digitalization for a sustainable future.

1. **Digitalization from the perspective of human history – a new era is emerging**. *Homo sapiens* is a young species that emerged over 250,000 years ago. Our species experienced a first cognitive revolution 70,000 years ago when fictive, complex languages emerged. Complex language distinguishes us from all other species. It has helped us learn and accumulate knowledge based on communication and to combine our own perceptions of the world with the perspectives of many others. This revolution triggered an unprecedented capability to accumulate knowledge, to cooperate, to develop shared intentionalities, and to build highly complex social systems – from small groups in the Stone Age, to the first larger cities some 5,000 years ago, to the globalized economic, technological, and social systems of the world we live in today. Language, communication, cognition, and cooperation capabilities are the starting point of the cultural evolution of our species (Messner & Weinlich, 2016).

   Accumulation of knowledge and intelligence is a major common asset of humanity and it is truly renewable. Over the last 10,000 years, humanity has moved through two fundamental civilizational phases. The Holocene period, which began after the last Ice Age (some 10,000 years ago), was characterized by a long sequence of warm years, relatively calm conditions, and a stable climate. During this period, the Neolithic Revolution led to the cultivation of plants and domestication of animals, which in turn resulted in the emergence of villages, the first small-scale societies, and early civilizations.

   Two hundred years ago, the Industrial Revolution radically changed humanity through an explosive accumulation of knowledge. The invention of machine-supported and labor-saving work enhanced manual skills and capacities, resulting in a hundredfold increase in productivity through, for example, technological innovations, the uptake of fossil fuels, steam, steel, and mechanization. The Industrial Revolution resulted in a globally connected economy, an emerging global society, globally networked infrastructure and mobility, vast increases in productivity, and – for some of the global population – significant wealth creation. At the same time, the Industrial Revolution also resulted in unequal distribution patterns and major Earth-system changes that have become real threats to human civilization. Humans have caused a very rapid and dramatic transformation of environmental conditions, threatening a dramatic departure from the Holocene conditions that were so favorable for human development. This emerging new era in Earth's history has been termed the Anthropocene (Crutzen & Stroemer, 2000).

   The Digital Revolution, which began in the 1950s and is currently accelerating exponentially, marks a third civilizational revolution. Digitalization is a powerful multiplier of trans-scalar economic, social, and cultural connectivity, merging physical and virtual realities. Even more importantly, it is characterized by the creation of technical systems (e.g., artificial intelligence and deep learning) with cognitive capabilities that already enhance human cognition, and will eventually complement, sometimes replace, or perhaps eventually far surpass human cognitive capabilities, at least in certain functional areas. Recently, real numbers emerged spontaneously without being explicitly programmed to do so in a "biologically inspired deep neural network that was merely trained on visual object recognition. This performance showed all the characteristics of human and animal number discriminations as predicted by the Weber-Fechner law" (Nasr et al., 2019).

Sustainability transformations need to be developed, implemented, and rethought in this newly configured context of the Digital Age, which we might call the Digital Anthropocene (WBGU, 2019). What are the key elements for describing the opportunities, turbulences, and challenges ahead, and how can humanity render the Digital Anthropocene an era of sustainability for all?

2. **Digital technologies can enable a disruptive revolution toward a Sustainable Anthropocene.** The previous TWI2050 report and many studies (Acatech, 2015, 2016; TWI2050, 2018) show that digital technologies can, at a much faster rate than ever before, help (as enablers) decarbonization across all sectors (e.g., energy, mobility, and industry), and promote circular and shared economies, dematerialization, resource and energy efficiency and sufficiency, the monitoring and conservation of ecological and other Earth systems, the protection of the global commons, and sustainable behaviors. However, this is not an automatic process and will not happen by itself. In fact, until now, the opposite has generally been the case: the digital transitions of recent decades have perpetuated, or even triggered, resource and greenhouse-gas-intensive growth patterns. Technology has not yet been mobilized toward sustainability transformations. Therefore, a radical reversal of current trends is needed to reduce the disruptive potentials of digitalization and create pathways toward sustainability. The report TWI2050 (2018) (see Box 1) highlights Six Fundamental Transformations (Figure 2) needed to achieve the 17 SDGs and long-term sustainability for all: (i) *Human Capacity & Demography; (ii) Consumption & Production; (iii) Decarbonization & Energy;* (iv) *Food, Biosphere & Water*; (v) *Smart Cities;* and (vi) **the Digital Revolution** (see section 1).

   Since many transformations toward sustainable development will take a long time to run their course, the SDGs should be regarded as mid-points toward achieving sustainable development by 2050 and beyond. There is an urgent need for corresponding regulatory policies, incentives, and shifts in perspectives, which currently only exist in a small number of sectors and a few countries. We propose Six Essential Mechanisms that can link digital dynamics with sustainability strategies to enable the Six Fundamental Transformations: (i) *shifting innovation vision and patterns* by creating sustainable digitalization perspectives in the science, research, and R&D communities; (ii) *mobilizing market forces* by getting the prices right, for example, through carbon pricing and ecological tax reforms that incentivize the mobilization of digital innovations in support of sustainable solutions; (iii) helping to *shift markets* and planning processes in a sustainable direction by using digitalization to visualize and establish transformation roadmaps that include sharper definitions of clear goals and milestones for energy, mobility, land use systems, cities, and industrial sectors; (iv) *investing in digital modernization programs at the state level* to massively increase digital knowledge in public institutions in order to build governance capacities in the Digital Anthropocene; (v) *transforming sustainability research* by supporting and scaling up strong networks with the digital research communities; and (vi) *creating dialogue structures* with the private sector, civil society, science, and the state to develop joint perspectives on institutional, social, and normative guardrails in the Digital Anthropocene.

3. **Governance is urgently needed – the disruptive dynamics of digitalization are challenging the absorptive capacities of our societies, possibly multiplying the already alarming trends of eroding social cohesion.** If not shaped appropriately and geared to the 17 SDGs of the 2030 Agenda and the associated Six Fundamental Transformations, digitalization could magnify already existing problems in many societies. We see four major challenges or "slippery slopes": (i) *inequalities* (e.g., in the labor market, in education systems, and in the division of labor at the international level) and dissipative forces within society could further increase; (ii) *economic, and by extension political, power* could become even more concentrated (consider, for example, the significance of the "big five" – Amazon, Apple, Facebook, Google, Microsoft for digital transformation); (iii) *data sovereignty and civic rights* could be restricted further and the monitoring of citizens and consumers ("social scoring") stepped up, especially in authoritarian societies and irresponsible companies; and (iv) *governance capacities* of public organizations could erode further, since, for example, it is already very difficult to regulate big digital business and essentially impossible in virtual environments, particularly because digital knowledge is still very limited in most governments and public institutions.

Figure 2. TWI2050 focuses on Six Transformations that capture much of the global, regional, and local dynamics and encompass major drivers of future changes: (i) Human Capacity & Demography; (ii) Consumption & Production; (iii) Decarbonization & Energy; (iv) Food, Biosphere & Water; (v) Smart Cities; and (vi) the Digital Revolution. Together, they provide a people-centered perspective, enabling the building of local, national, and global societies and economies that secure the wealth creation, poverty reduction, fair distribution, and inclusiveness necessary for human prosperity. They are necessary and potentially sufficient to achieve the SDGs if addressed holistically and in unison. Source: TWI2050 (2018).

Box 1. The World in 2050 Initiative (www.TWI2050.org)

Today, no science-based pathways have been developed for successfully achieving all the SDGs simultaneously. The global transformations necessary to achieve the SDGs urgently need a robust scientific foundation and fact-based way forward. The World in 2050 (TWI2050) is a global multiyear, multi-stakeholder, interdisciplinary research initiative designed to help address these issues. TWI2050 is a partnership between science and policy that aims not only to contribute to this understanding, but also to develop science-based transformational and equitable pathways to sustainable development that can provide much-needed information and guidance for policymakers responsible for the implementation of the SDGs, such as the UN High-level Political Forum on Sustainable Development.

Using an integrated and systemic approach, TWI2050 addresses the full spectrum of transformational challenges related to achieving the 17 SDGs. It seeks to avoid potential conflicts among them, to reap the benefits of potential synergies, and to reach the just and safe target space for people and planet by 2050 and beyond. This approach is the first goal-based, multi-model quantitative and qualitative integrated analysis that encompasses the full set of SDGs. The successful identification of sustainable development pathways (SDPs) requires a comprehensive, robust approach that spans disciplines and methodologies, and that can deal with non-linearity. The consortium under the umbrella of the TWI2050 initiative has been put together to reflect these necessary competencies. A core strength that sets TWI2050 apart from other initiatives contributing to scientific knowledge creation for the SDGs is its competence in Integrated Assessment Modeling (IAM) and pathway development. However, to best tackle sustainable development challenges in the 2030 timeframe and beyond, TWI2050 seeks to further deepen and better integrate knowledge and analytical capacity across social, political, technical, and Earth systems.

A starting point for analyzing pathways toward goals is to establish an agreed framework. TWI2050 proposes an overarching framing narrative and quantitative and time-bound targets and indicators that set the outer boundary conditions for the transformation of the world between now and 2050 through the SDGs and the Paris Agreement. The objective is to mobilize the international research community to explore multiple

SDPs by applying backcasting analyses of how to achieve the goals in the framing narrative at multiple scales. At an overarching level, the objective is to achieve all SDGs by 2030, and by 2050 to continue meeting all SDGs in an evolving prosperous and just world for all while stabilizing the Earth system within planetary boundaries and remaining cognizant of the dynamics of Earth and human systems on a longer time horizon to 2100.

The TWI2050 framework (Figure 3) includes qualitative and quantitative elements and consists of the following: (i) a broad transformational narrative; (ii) targets and indicators for 2030 and 2050; and (iii) specific SDPs that include quantitative elements based on modeling approaches (TWI2050, 2018). These are paired with governance elements that induce the transformations and are thus an integral part of the overall framework. There can be many alternative pathways that explore branching points, lock-ins, resilience, inclusiveness, cooperation, and differing transformational dynamics. The TWI2050 framework is designed to allow modeling and analytical groups to identify and explore a portfolio of measures needed to achieve all SDGs, and to jointly account for synergies and trade-off. With such common goals and agreed common assumptions, the framework facilitates comparison between results.

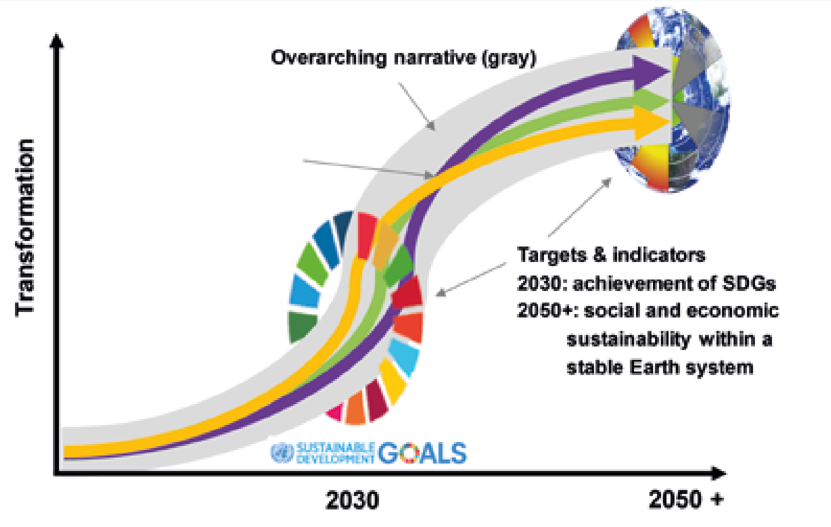

Figure 3. An illustration of the TWI2050 conceptual framework. Two sets of science-based, normative targets provide boundaries for the transformation toward a sustainable future. The first are symbolized by the SDGs for 2030 and the second for 2050 and beyond, and symbolizes the achievement of a just and equitable future for all on a resilient planet. The gray band illustrates the overarching narrative that indicates how the future is connected to the present. The narrative is about what needs to change to achieve the transformation toward sustainability by 'backcasting' from the normative targets. Also shown are alternative SDPs that provide model-based quantifications of the transformational changes. They can be interpreted as alternative realizations of the overarching narrative. Source: TWI2050 (2018).

At the same time, digitalization could also help to tackle these four slippery slopes. There are, however, very few instances of successful processes for shaping and governing digitalization around the world. The key question is whether digitalization in its current form is amenable to "social steering" without new governance and policies. Accelerated technological developments threaten to overwhelm citizens, institutions and governments alike.

4. **The Digital Revolution opens new doors to a quantum leap of human civilization – the post-2030 Agenda era is already starting.** Development pathways will encounter uncertainties, deep and digitally driven societal and economic reconfigurations, and lock-ins that will emerge over the next decade. Policymakers, researchers, companies, and civil society actors must intensify their efforts to understand and explain the multiple effects of digital change and to anticipate far-reaching structural change so that they can create a basis for shaping the digitalization process and gearing it toward sustainability transformations. Digital disruption is locking us into new economic, societal, and cultural realities and challenges. Virtual reality, artificial intelligence, deep learning, big data, and games are increasingly being used in planning and scenario-building processes, improving our cognitive capacity to understand the implications of decisions in complex socioecological systems and the

multiple perspectives that can guide better decisions. These are powerful tools for supporting transformation processes.

Autonomous technical and decision-making systems, based on learning machines and general purpose artificial intelligence, will fundamentally transform all areas of society and the economy in the near future (Acatech, 2015; Barrat, 2013; Brynjolfsson & McAfee, 2014; Schwab, 2016; Bughin et al., 2017; Tegmark, 2017; Villani, 2018, DiPLo, 2019). By processing enormous volumes of data, artificial-intelligence-based devices and machinery will steer production processes, traffic, and financial flows, revolutionize medical diagnostics and treatments, change the way insurance companies make decisions, generate behavioral forecasts for individuals and groups (Domingos, 2015), and make decision documents available to parliaments and governments. The evolution of Human intelligence has had no rival since *Homo sapiens* emerged. Now it is being supplemented by artificial intelligence, which, in some areas at least, is far superior to human analytical capabilities. Linking human and artificial intelligence and creating "meaningful artificial intelligence" geared to the goals of sustainable human development (Villani, 2018) is set to become a major task for humanity in the first half of the 21st century. The next decades will be characterized by numerous digitally driven, deep structural changes and related uncertainties.

Sustainability pathways need to be developed, shaped, and governed within the context of deep societal transitions and high degrees of uncertainty. Asking the right questions is important. How can we reduce the error rate of (globally) connected and increasingly self-organizing technical infrastructure and make it more robust? How can our legal systems and institutions keep pace with accelerated technological change? How can the unintended effects of private investment in the development of self-learning technical systems and virtual environments be understood by citizens and governments, and be geared to, and shaped in accordance with, our standards systems? How can prosperity be multiplied through automation, while simultaneously observing the principle of leaving no one behind? What are the implications of the technological revolution for the poorest developing countries (Tegmark, 2017)? And even more far-reaching questions: Where is the line when it comes to using technology to alter, improve, and manipulate people's cognitive, physical and emotional capacities? What ethical guardrails should be put in place in the discussion about the transformation of humans and human enhancement (WBGU, 2019) and autonomous systems (e.g., IEEE Global Initiative on Ethics of Autonomous and Intelligent systems[2])? Which tasks can intelligent machines manage better than humans (Gluckmann and Kristiann, 2018)? Where and how should human judgement play a role? How will machine learning transform (democratic) human decision making? How can we avoid creating digital, self-organizing systems and networks, with potential control over human behavior, that could be misused by powerful actors (Renn, 2019; WBGU, 2019)? These questions, all of which relate to still unknown territory, are not described in the 2030 Agenda; however, they illustrate the magnitude of the formative tasks associated with the digital transformation in the context of building a sustainable global society.

Based on a comprehensive assessment of digital dynamics, the German Advisory Council on Global Change (WBGU, 2019) identifies seven major digital tipping points that are related to the four slippery slopes outlined above. These tipping points reflect characteristics of our current societies, but they also take into consideration the digitally driven and deep configurations of our economic, social, political, and cultural systems over the next 10–30 years, and they identify possible developments that will potentially destabilize our societies: (i) exceeding planetary boundaries and triggering tipping points in the Earth system based on digitally driven resource- and emission-intensive growth patterns that are not redirected toward sustainability by political guardrails; (ii) disempowerment of individuals, including fundamental threats to privacy and citizen rights, comprehensive digital surveillance of people, and digitally empowered authoritarianism or totalitarianism; (iii) undermining of democracy and inclusiveness by normatively and institutionally automated decision-making systems, which are already being used in a growing number of areas, especially in the digitalized private sector; (iv) national, regional, and even global dominance of private companies, undermining democratic control and driven by further data-based power concentration; (v) disruptions of labor markets by comprehensive automatization – raising concerns that human labor is becoming irrelevant for the economy; (vi) deep division of the global society resulting from digital opportunities mainly being mobilized by a transnational elite; and (vii) uncontrolled human-enhancement or artificial evolution methods that will lead to large-scale transformation of humanity.

5. **The paradox of the Digital Anthropocene: digitalization is creating essential preconditions for the Six Fundamental Transformations toward sustainability and is also endangering them.** Beyond the uncertainties and possible societal tipping points of the Digital Anthropocene, there are unprecedented digital opportunities and digital game changers that can make the transformations toward sustainability happen. First, *technologically*,

2 https://ethicsinaction.ieee.org

the shift from linear to circular economies is now within reach. We could decouple wealth creation from resource consumption, emissions, and ecosystem degradation. Comprehensive monitoring of the planet is becoming possible and could help to conserve and protect global ecosystems.

Second, *knowledge breakthroughs and explosions* offer unprecedented new potential for humanity, provided that the digitalization process and associated technologies (e.g., new composite materials, nanotechnology and nanobiotechnology, genetic engineering, synthetic biology, biomimetics, quantum computing, additive manufacturing, and human enhancement) are shaped appropriately. Artificial intelligence, deep learning, and big data will also transform science and open new doors to a next phase of human civilization. Virtual access to the most advanced global knowledge about humanity and the planet could be used to achieve a fair, decent, and safe future for everyone.

Third, digital dynamics could enable *cultural, institutional, and behavioral innovations*. Transnational communication networks could help to build a networked global society, transnational governance mechanisms, global common goods perspectives, cultures of global cooperation, and transnational identities, and they might create new (sub-)cultures. Virtual networks of people from around the globe might improve our understanding of cultural diversity. Virtual realities will enable humans to "visit," understand, enjoy, and "feel" global ecosystems without long-distance travel. In parallel, new options are quickly expanding for democracy-promoting mechanisms through the use of digitalized "voting" procedures, including online checks for local decision making about practical but important governance issues related to transformation and reform preferences (Ekenberg et al., 2017). These emerging innovations present potentially positive characteristics of a new age of humanity.

The printing press, which from an artificial intelligence perspective may appear to be a rather small step in human development, was the innovation that enabled the Enlightenment, scientific investigation, democracy, and the Industrial Revolution. Might we see a new kind of Enlightenment as a result of combining artificial and human intelligence with human empathy, intentionality, and social intelligence? How can we exploit the potential of digitalization and the associated wealth of new knowledge in order to tackle the major challenges facing humanity in the 21st century, while avoiding the daunting risks of accelerated technological changes running out of control? These questions make clear that fundamental transformations in our systems of education and global knowledge transfer are urgently needed.

6. **Human enhancement and augmentation leading to a transformation of *Homo sapiens* into *Homo digitalis* – the uncertain future of our species.** Digital technologies and their convergence will certainly enhance and augment human physical and cognitive capabilities. Human performance has improved enormously over the last century, with unprecedented achievements in health, sports and knowledge. The human life span, which has doubled over the last century, could further increase, perhaps without limits, through digital enhancement and augmentation. The use of artificial organs and limbs will undergo a quantum leap, as will completely new enhancements such as exoskeletons and physical augmentation.

   The major challenge will certainly be cognitive enhancements. The Internet and mobile applications already provide important enhancements to our cognitive capabilities, and they constitute a kind of external memory and knowledge depositories. The danger is, of course, a misuse and diffusion of alternative realities that in the future may be fundamentally enhanced by virtual realities. The loss of privacy and control of one's data and personality are already a challenge, but they may pose a huge danger to democracies and free-thinking people in the future should new bionic and human-enhancement systems fall into the wrong hands or undergo evolution beyond human control. The loss of control and the impossibility of social steering might be the biggest dangers of the Digital Anthropocene.

   Nevertheless, digitalization offers incredible possibilities for freeing humanity from physical toil and for augmenting and enhancing cognitive and physical capabilities. The old science fiction vision of machines making machines is a reality today, but machines controlling humans rather than enhancing and augmenting them is a real danger. The future is open, but the direction of change is unknown. Steering change and possibilities toward the Sustainable Anthropocene for all must, therefore, become the highest priority.

7. **Understanding and overcoming the "retarding moments" (WBGU 2019) of innovation breakthrough.** Historically, large-scale, fundamental, and disruptive technological innovations often resulted in societal and economic turbulence, or even crises, backlashes, or conflicts, before societies learned to mobilize their welfare potential (TWI2050, 2018).

   Again, the printing press (between 1452 and 1456, the 42-line Gutenberg Bible was published, marking the invention of the press) was obviously a crucial precondition for the Age of Enlightenment, the emergence of science, and industrialization; however, initially the large-scale diffusion of printed leaflets was directed to sow hatred, paving the way for the disastrous Thirty Years' War in Europe. Industrialization had the potential to create unknown wealth for many people. But it initially resulted in large-scale exploitation, social conflicts, and class struggles, before (albeit after two world wars) industrial and market mechanisms were embedded in democratic institutional structures and welfare state mechanisms, helping to mobilize the welfare potential of industrialization for many people and nations (primarily in Western countries). However, the democratic welfare state itself, although solving the social and power challenges of the past, created new, unforeseen crises. The great industrial acceleration produced the Era of the Anthropocene, with the transcendence of planetary boundaries leading to tipping points in the Earth's ecological system.

The challenge in the present era of digitalization is to resolve the immense sustainability problems of the Digital Anthropocene, while at the same time understanding the newly emerging challenges of artificial intelligence, automated decision-making processes, and virtual spaces. How far can humanity go with human enhancement and augmentation? How can we interact productively, constructively, and "humanly" with artificial intelligence? How can we keep democratic control over the waves of technological change that are still poorly understood? How can we protect citizen rights, human rights, and individual rights in an age of big data analysis and global communication networks? Where digital advances meet authoritarian governments or powerful business actors, democracy and civil rights are at stake. The scale of these challenges is large: How can we learn to overcome the historical law of "retarding moments" of radical and disruptive technological innovations, without experiencing deep crises in the first place?

8. **Building responsible knowledge societies capable of taking action toward sustainability in the Digital Age**. There is no silver bullet to shape and govern the Digital Revolution toward sustainability, because the future is inherently indeterminate. The challenge is to build resilient, adaptive, creative, knowledgeable, and inclusive "Responsibility Societies" (WBGU, 2019). We will be able to exploit the opportunities of digitalization, virtual realities, and artificial intelligence, and to curb their potential risks and link the digital and the sustainability transformations, only if the digital and sustainability research communities converge. However, such a convergence is still a long way off. Connecting the greatest innovative dynamics in human history with the major transformation toward sustainability, in order to stabilize the planet and enable a good life for 9–10 billion people in the 21st century, will require tremendous efforts, swift actions, institutional changes, huge investments, patience, and a clear normative framework.

   The following cornerstones create an interdependent system architecture that will help to manage the harmonization of the digital and the sustainability transformations:

   1. *Education*: People need to be enabled to understand and shape the emerging digital shifts.
   2. *Science*: New knowledge networks must create transformative knowledge to integrate digital and sustainability-oriented transformations, avoid the digital tipping points, and build normative frameworks for the epoch of convergence between human and machine intelligence.
   3. *Modernizing states*: Public institutions are not at all prepared to comprehend and govern digital dynamics. Large-scale modernization and educational programs are necessary in this regard.
   4. *Experimental spaces*: Learning-by-doing and using is the main principle of technology and institutional diffusion, especially during the early innovation phases. Creative spaces need to be established to nurture fast learning and should include the possibility for "crazy ideas and start-ups" to gain ground.
   5. *Global governance*: The Digital Revolution has global impacts on how alliances are built. Modernizing the UN, for example, will be shaped by the Digital Age.
   6. *"New Humanism"* (WBGU, 2019): The 2030 Agenda can be seen as the new "social contract" for the world, transforming our values and visions of the future beyond 2030 and toward sustainability for all. This implies new normative goals for the future of the people and the planet, new development models detached from materialism and negative externalities for the environment and the Earth's system, and new normative guardrails for all.

9. **The need for urgency from a 2030 Agenda perspective- only 10 years to 2030.** There are only 10 years to go to mobilize and leverage the digital opportunities to build sustainable societies. Trend reversal is urgent as the world is at a crossroads. We have only 10 years to learn how to manage and positively use the societal impacts of digitalization and artificial intelligence, to merge virtual and physical spaces and realities, and to avoid further erosion of social cohesion. If we do not manage to get the two fundamentals right – that is, digitalized green economies, and stable, equitable, open digitalized societies – the world will run into a serious impasse instead of developing further sustainability transformations. And if that happens, the window of transformation toward

a Sustainable Anthropocene would be closed. Time is a very precious and scarce resource that must be used wisely.

Clearly there are many societal challenges associated with increasing digitalization, which, if not managed carefully and thoughtfully, have the potential for a significant counter-revolution. However, it is equally clear that advances in technology offer huge societal benefits, as long as they are explicitly directed toward a sustainable future. The potential for huge progress in education, health, equity, and prosperity, while reducing environmental degradation, is undeniable (as explored in the examples throughout this report). Moreover, there will be societal impacts brought about by significant changes to how and where we live and work, how we spend our increased leisure time, and how we interact with other members of our immediate, local, and broader communities. Ensuring that these impacts are positive is imperative.

Societies, and their governments, are at a critical crossroad. We face decisions about the type of future we want – assuming, of course, that the current trends can be managed or regulated at all, with the present pace of innovation creating new tools and techniques well ahead of the creation of guiding norms and policy, in fact ahead of any public awareness about them. In the absence of a thoroughly examined, deliberate path for the introduction of new technologies, the consequences to the public good and to natural resources are often confronted only after the fact. Frequently, these consequences are confronted only when the damage is large enough and cannot be ignored, and when the public feels deceived. However, the Digital Revolution can help provide the tools to inform the public about the positive attributes of new technologies and to engage their support up front. While public support is essential for the realization of the full potential of new technologies, public concerns will place constraints on the realization of their full commercial and financial potential.

1 Six Fundamental Transformations for a Sustainable Future for All

The transformations to a sustainable future for all imply deep structural changes, profound reforms of institutions, shifting mental maps and norms, changing patterns of human behavior, widespread awareness raising and mobilization, the adoption of a complex adaptive systems approach to sustainability issues, and unprecedented problem solving. As transformative change is needed, transformative governance is required as well.

In view of the complexity and breadth of the changes occurring, and those to be expected, it is essential that we begin an effort to move beyond the sectorial and fragmented approach adopted by much sustainability research thus far. Rather than only investigate the separate roles of water, or food, or energy, or even the water-food-energy nexus, we should design an approach that aims at truly integrating all possible affected domains, focuses on trade-offs and co-benefits, and generally takes a holistic perspective that is at the core of the 2030 Agenda. Another synergetic approach of the 2030 Agenda strives to harness science, technology, and innovation to accelerate progress. The Digital Revolution is at the center of the perspectives of science, technology, and innovation. The holistic approach implies that the full complexity of the dynamics involved in each domain of social, social-environmental, and social-environmental-technological interaction – from the basic values and world view of individual societies and cultures, to their ways of interacting, their institutions, their governance, and so forth – will be given space to be played out, and that there will be room for a wide range of aspects about the characteristics of both present and future societies to be considered.

To move in that direction (at least for the moment, as we are still not able to deal with the full complexity of the total systems involved), the authors of TWI2050 (2018) have focused on Six Fundamental Transformations that capture much of the global, regional, and local dynamics. They encompass the major drivers of future changes, yet they also reduce the complexity of the 17 SDGs. The Six Fundamental Transformations are: (i) Human Capacity & Demography; (ii) Consumption & Production; (iii) Decarbonization & Energy; (iv) Food, Biosphere & Water; (v) Smart Cities; and (vi) the Digital Revolution.

Arguably, the Six Fundamental Transformations are necessary to achieve the SDGs by 2030, and to achieve sustainability by 2050 and beyond. Each transformation will require unprecedented governance efforts, and each implies deep societal, cultural, and normative dynamics of change.

The Six Transformations are not intended to be a new clustering of the 17 SDGs nor to be a "reduced form" of the SDGs and their 169 targets. Rather, they are intended to describe systemic and integrative changes that are related to all SDGs, as illustrated in Figure 2. Rather than being merely interlinked and interdependent with all the SDGs, they are arguably at the center of the great transformation toward sustainability and fundamental in "turning the tide" of change.

Why these Six Fundamental Transformations?

Principally, the Six Transformations provide a people-centered perspective: their objective is to build local, national, and global societies and economies that secure wealth creation, poverty reduction, fair distribution, and inclusiveness necessary for human prosperity in any society and any region of the world. While these objectives may be pursued differently in different contexts, there are some domains of action which appear to be universal. These domains include: (i) institutions that enable and improve human capacities and capabilities by ensuring access to education and health care, fair labor markets, the universal rule of law, and the means to manage aging societies; (ii) the essential and strategic infrastructure of any local, national, or global economy and society, such as energy, food systems, cities, settlements, and mobility systems; (iii) production and consumption systems where deep transformations need to take place to create wealth and ensure a good work-life balance; and (iv) science, technology, and innovation that are essential for further progress toward achieving the SDGs (Box 2).

The Six Transformations nicely capture these domains of action that allow the achievement of human wellbeing in all its dimensions. There are, however, further arguments for the selection of precisely these Six Transformations. All of them are associated with powerful dynamics that can result in very different development outcomes for humanity – both positive and negative. At the same time, all these processes take place in systems whose evolution depends on governance, values, policy tools, and so on; that is, these processes can be managed, and the outcomes depend on choices made by humans. Moreover, as the Six Transformations interact essentially with all the SDGs, they also provide an entry point for achieving all the SDGs in a manageable way.

Box 2. Key Messages of the Six Transformations[1]

Substantial advances in human capacity are needed through further improvements in education and health care. Education and health are instrumental for enabling people to live self-determined lives, find decent work, and generate income to sustain themselves, but also to undertake climate change mitigation and deal with environmental problems. The ambitions go hand-in-hand with the goals to end poverty in all its forms and to reduce global inequality.

Responsible consumption and production cut across several of the other transformations, allowing us to do more with less. Evidence shows that it is possible to reduce consumption of resources considerably by taking a more service and circular economy-oriented approach with respect to mobility, housing, food systems, and other sectors of our economies. Reductions in demand leverage the potential of large savings at different stages of the supply chain.

It is possible to decarbonize the energy system while providing clean and affordable energy for all. Pathway analysis shows that energy efficiency, increasing the share of renewable energy, electrification, and carbon capture and storage all play a key role in fully decarbonizing the energy system by 2050, while providing access to modern energy for all. Achieving the Paris Agreement is still possible but only if combined with a focus on a broader set of SDGs.

Achieving access to nutritional food and clean water for all while protecting the biosphere and the oceans requires more efficient and sustainable food systems. It is possible to meet the needs of a growing world population while at the same time limiting the food system's environmental impacts by combinations of increasing agricultural productivity, reduction of waste and losses, and moves toward a less meat-intensive diet. The highest priority is to provide healthy and affordable food for all and thereby to eradicate hunger. Heathy diets and lifestyles are also essential for reducing global obesity levels.

Transforming our cities will benefit most of the world's population. Pathways show that by 2050 around two thirds of the human population will live in urban areas. Sustainable cities are characterized by high connectivity and "smart" infrastructure, enabling high-quality services with a low environmental footprint. Transforming slums into decent housing is feasible, and in a way that has low energy and material requirements. Good city design, sustainable lifestyles, empowered local actors, and participatory approaches that avoid one-size-fits-all solutions are needed to achieve this transformation to sustainable cities.

Science, technology and innovations are a powerful driver, but the direction of change needs to support sustainable development. The Digital Revolution symbolizes the convergence of innovative technologies, many of which currently make ambiguous contributions to sustainable development, simultaneously supporting and threatening the ability to achieve the SDGs. There is an urgent need to bring the sustainability and the digital and technology communities together to align the direction of change with the 2030 Agenda and a sustainable future beyond. It is also necessary to implement forward-looking roadmaps and governance structures that allow the mitigation of potential trade-offs of the revolution in science, technology, and innovation, particularly in relation to this revolution's impact on work, social cohesion, and human dignity.

1 Full descriptions of the Six Fundamental Transformations can be found in TWI2050 (2018), www.twi2050.org.

2 Report Outline

The focus of this report is on the sixth transformation: **the Digital Revolution**. Although the Digital Revolution is arguably the single greatest enabler of sustainable development, it has the potential also to create many negative externalities, such as the further transgression of planetary boundaries. Progress on the SDGs will be facilitated if we can build and implement detailed roadmaps for science, technology, and innovation, at levels that range from the local to the global (Colglazier, 2018). Science, technology, and innovation are forceful drivers of changes connected to all the SDGs, especially at this point in history. The Digital Revolution has an ongoing and twofold major impact: it provides entirely new capacities, thus serving as a major force in shaping both the systemic context and future solutions; at the same time, it has the potential for strong societal disruption if not handled carefully and cautiously.

This report does not simply point out all the positive potential benefits that digitalization can bring to sustainable development. It also highlights the potential negative impacts and challenges going forward, particularly for those impacted by the "digital divide", most notably the poor in the developing world. Moreover, it outlines the necessary preconditions for a successful digital transformation; these preconditions include prosperity, social inclusion, environmental sustainability, and good governance. Importantly, this report sets out some of the dramatic social implications associated with an increasingly digital future. It covers a topic that has hitherto not been sufficiently dealt with in debates about sustainability and the Digital Revolution. In particular, the consideration of governance has yet to be fully addressed. The policies, institutions, and governance arrangements necessary for achieving sustainable development have yet to be created and promoted.

3 The Digital Revolution

The Digital Revolution can facilitate sustainable development through ongoing advances in areas such as artificial intelligence, connectivity (the Internet of Things), digitization of information, additive manufacturing (such as 3D printing), virtual or augmented reality, machine learning, blockchain, robotics, quantum computing, and synthetic biology. As in the Industrial Revolution, where explosive development was initiated through the convergence of steel, steam and railways, coal, and new manufacturing processes for textiles and other goods, so the convergence of these new digital technologies could be even more profound. The Industrial Revolution resulted in great winners and losers; the same could be the case for the Digital Revolution.

Technological change plays a key role in long-term social transformations. With the advent of "knowledge societies", many current technological transitions favor non-material and shared benefits that support human wellbeing.

The Digital Revolution is already reshaping work, leisure, behavior, education, and governance. In general, these contributions can have positive impacts on labor, energy, resources, and carbon productivity, and they can lower production costs, expand access to services, and dematerialize production.

Yet there are also clear dangers and downsides to the Digital Revolution, including the loss of jobs, inequality (Figure 4), and the further shift of income from labor to capital. With automation and advances in artificial intelligence and robotics, many more workers, even those who are highly skilled, may find their jobs and earnings under threat. While new jobs might replace old ones, the new jobs may come with lower real earnings and worse working conditions. The fears about increasing inequalities have given rise to renewed interest in a guaranteed minimum income.

The concern about growing inequalities reflects the current dominance of a handful of technology companies, such as the "big five" (Amazon, Apple, Facebook, Google, and Microsoft) or their Chinese counterparts (e.g., Alibaba and SinaWeibo). The same applies to specific sectors, such as agriculture and food systems, which are currently dominated by a few giant companies. This leads to concerns about if (and how) new technologies could be appropriated by different actors, or about whether the Digital Revolution will reinforce the concentration of resources, wealth, and power. For instance, in agricultural production, land concentration in the hands of large industrial agribusiness companies can be detrimental to small farmers.

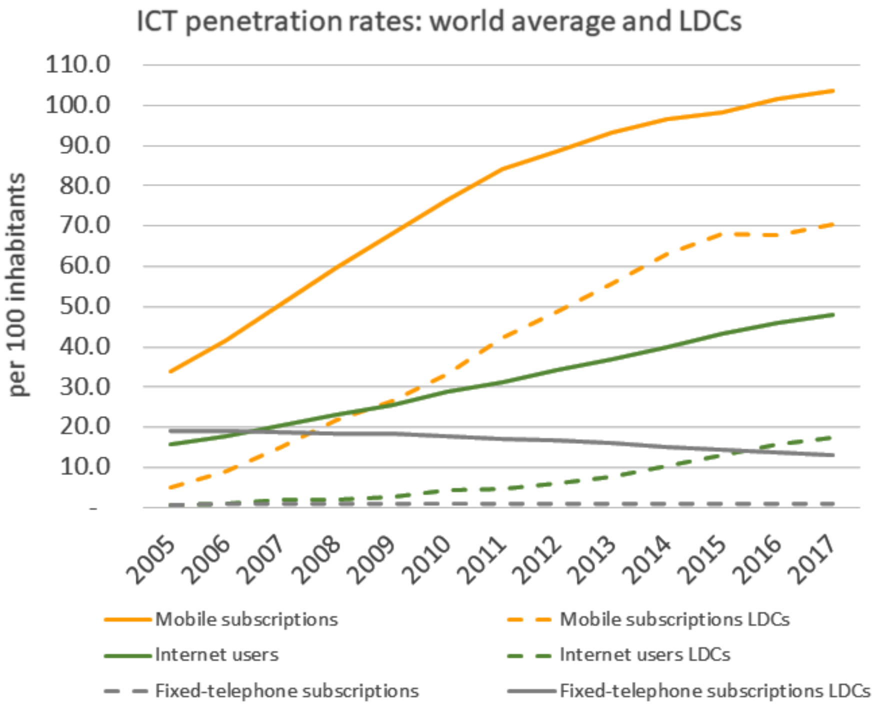

Figure 4. Penetration rates of novel information and communication technologies (ICT), such as mobiles and the Internet, have shown fast growth rates. They now reach more people than previous technologies such as fixed-landline phones. Inequalities persist: World averages are shown as solid lines, and the averages of least developed countries (LDC) are given as dashed lines, showing that inequalities persist. Source: Data from ITU (2018).

There are several other perceived threats from the Digital Revolution. Digital identities can be stolen, or artificial identities can be created. Digital information can be leaked, especially with the diffusion of 3D printing where complete information about manufacturing is stored digitally and could be used to circumvent export and import barriers by manufacturing locally. Governments and private businesses can invade privacy and monitor individuals against their will or without their knowledge. A few digital portals may use their advantages in amassing big data to gain a dominant monopoly position in their respective markets (e.g., e-commerce, digital advertising, social media, cloud services). Cyberattacks or cyberwarfare can interrupt or degrade private and public service delivery. Social media can be manipulated, undermining democratic processes. The personal use of online technologies can be addictive and cause the onset of depressive disorders. Special dangers relate to advanced weaponry. The most fundamental question is whether the Digital Revolution, as a self-evolving evolutionary process that has generated huge global monopolies, is even amenable to "social steering".

The Digital Revolution will have even deeper impacts on our societies, creating new sustainability-related concerns. General purpose artificial intelligence and other digital technologies will be increasingly used in decision-making processes embedded in devices (like self-driving cars), in our economies (in banks, trading firms, stock markets), and in our societies (in courts, parliaments, health-care organizations, and security organizations such as the police and military). All of these have the potential to complement, substitute, and challenge human-driven decision-making processes. We need to learn to manage and control the next generations of artificial intelligence, machine learning, and (semi-)autonomous technical systems, and to align them with our normative settings. Moreover, the digital transformation will redefine our concept of ourselves as humans. In the Anthropocene, humans became the main drivers of Earth-system changes. In the Digital Anthropocene, humans will also start to transform themselves, enhancing cognitive and brain capacities. Humanity is moving toward new civilizational thresholds. Super-intelligent machines might even develop "lives of their own", with the capacity to enhance humans, but also to harm them.

To capture the benefits of the Digital Revolution while avoiding the many potential downsides, the digital transformation requires a comprehensive set of regulatory and normative frameworks, physical infrastructure, and digital systems. An essential priority should be to develop roadmaps for science, technology, and innovation to better understand the potential benefits and dangers of digitalization (Colglazier, 2018). The principles of a digital transformation that will advance sustainable development have yet to be deeply explored, but some of the likely priorities and example measures are shown in Table 1.

Research is needed to further the understanding of technology systems. By studying the patterns, drivers, constraints, and impacts of technological change, viable options and policies that will accelerate the transformation of society toward a sustainable future can be identified (Figure 5). While technological change will always occur, a high level of uncertainty will remain about the direction it will take and about which parts of technological innovation packages will succeed, for what purposes, and in whose interests.

Table 1. Principles for digital transformation

Principles for digital transformation	Example measures
Enabling digital infrastructure, further expansion, and innovations	• Universal access to high-quality, low-cost mobile broadband
Online services	• Online governance to support public services and participation • Online finance and payments to facilitate trade and business services • Regulatory security for online identity and privacy • Online national systems (or "platforms") for health care and education
Digital systems to increase efficiency of resource use	• Smart grids and Internet of Things for sustainable cities
Analytical packages for exploration and monitoring	• Income redistribution to address income inequalities arising from digital scale-up • Tax and regulatory systems to avoid monopolization of Internet services • Democratic oversight of cutting-edge technologies (biotech, nanotech, artificial intelligence, big data, autonomous systems) • Universal access to high-quality, low-cost mobile broadband education to avoid new digital divides and to develop capacities for sustainable digitalization • Aligning the emerging digital technologies and infrastructures with human norms and the paradigm of sustainable development

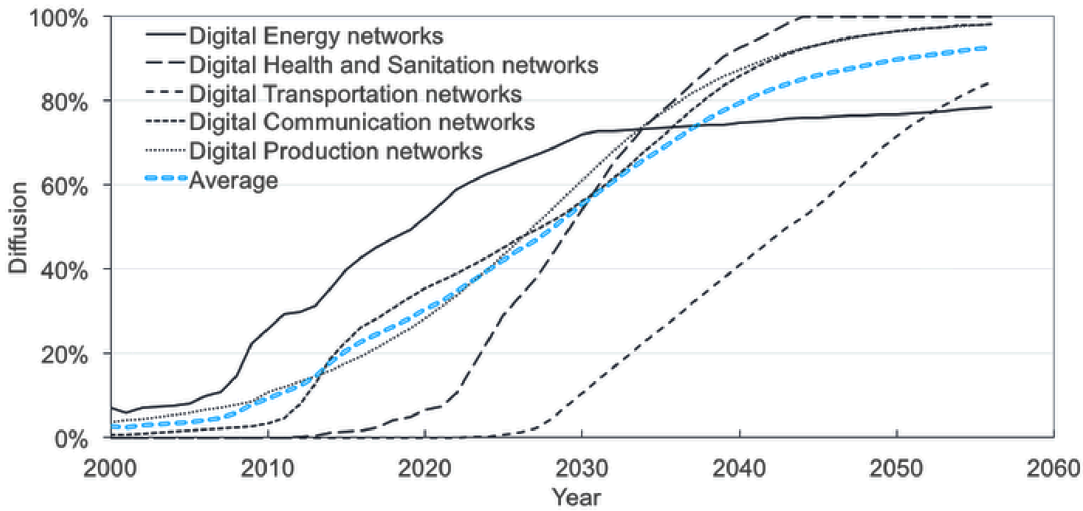

Figure 5. Future diffusion of exemplary and enabling digital infrastructures and technologies. By 2030, most of these networks, including the average of all, will exceed 50% diffusion, or the inflection point, meaning that the increase until then would be exponential. This illustrates the possibility of a very vigorous growth of digitalization in the world along with the emergence of new activities and behaviors. The opportunities and potential dangers are high and related to all SDGs. Source: Saniee et al. (2017).

4 Preconditions for a Sustainable Digital Revolution

The SDGs define sustainable development as a world in which all nations enjoy economic prosperity, achieve social inclusion, and ensure environmental sustainability. These economic, social, and environmental goals are sometimes called the "triple bottom line" (Elkington, 1994). The 2030 Agenda emphasizes that human, economic, social, and environmental development must be underpinned by good governance and global cooperation, often called the fourth pillar of sustainable development (Figure 6). Each of the 17 SDGs contributes to these four dimensions of prosperity, social inclusion, environmental sustainability, and inclusive governance.

These SDGs are "universal", in the sense that they apply to all nations and to all people within those nations. They are also "holistic", in that all 17 SDGs must be achieved in unison. In the oft-repeated language of the 2030 Agenda, no one (and no nation, region, or SDG) should be left behind. The 17 SDGs are meant to serve the task of providing a general and holistic frame for globally agreed goals and management directions concerning the key issues of our times. This has created a new "social contract" for the world.

The universality of the SDGs is unique, not only in establishing a moral standard for social inclusion and the right to decent lives for all, but also in underscoring the obligation of all nations to collaborate to meet global environmental targets, such as those of the Paris Agreement on limiting climate change. Because human activity has most probably already transgressed several indicators of a planetary safe space, all countries in the world must seriously face the need to bear their fair share of responsibility to achieve the globally agreed SDG targets.

For the Digital Revolution to play a positive role in deliberately and constructively supporting the sustainable development agenda, it, too, must operate within the preconditions and aims of prosperity, social inclusion, environmental sustainability, and inclusive governance.

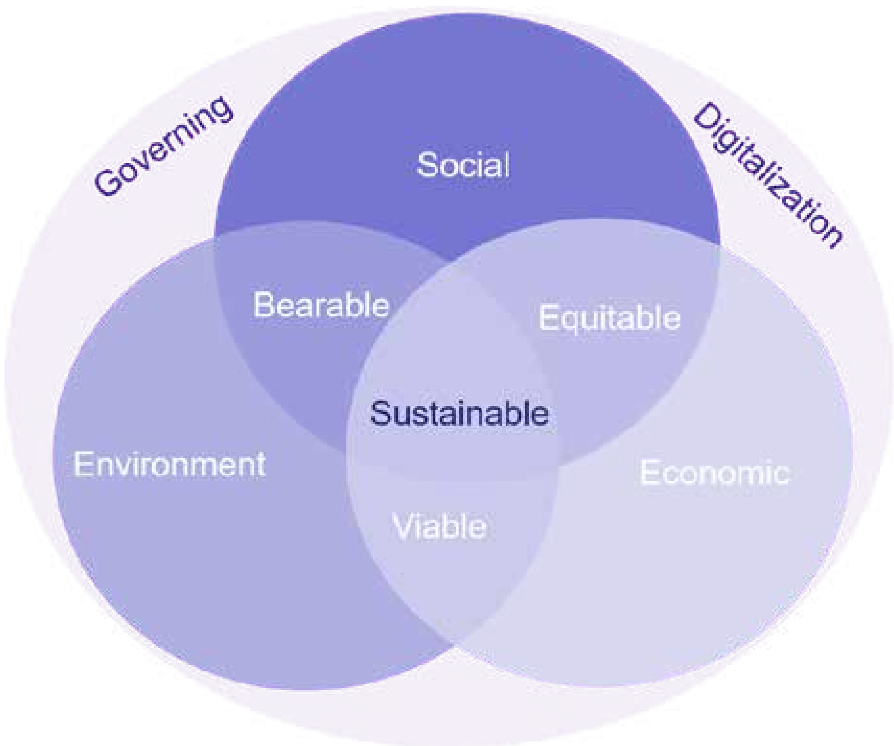

Figure 6. The SDGs represent a triple bottom line that can be illustrated as interconnected circles of people, planet, and prosperity. Governance is crucial to governing the process. Source: Adapted from Stone (2017).

4.1 Prosperity

The Digital Revolution clearly has the potential to drive global economic growth and improve human wellbeing, which, if shared equitably across the globe, could lead to increased prosperity for all. However, the major risk to such an outcome is the dramatic impact of digitalization on the nature and future of work. Although, historically, technology has created more jobs than it has displaced (Stewart et al., 2015) and is responsible for enormous productivity growth, there is no guarantee that this trend will continue in the future. Even if it does, it is likely that some will be left behind, especially those in low-skilled employment. Understanding what to do about those left behind by economic progress is becoming a pressing matter for policymakers. In the USA, the "last-mile" jobs are already occupied disproportionally by workers without a college education, and it seems that there is no land of opportunity without a high level of education (Free exchange, 2019). There is no clear immediate solution, and many countries are currently grappling with this problem, particularly in the developing world, which is likely to be most impacted. It will require a systems-wide holistic approach that takes into consideration developments across the Six Transformations for sustainable development with a special focus on education and human capacity.

Perhaps equally important is that it is increasingly clear that continued uneven and persistent economic growth is unsustainable in the long term, both environmentally and socially. We need to move from a planned obsolescence economic model of "take, make and dispose", in which most of the world's resources are wasted and end up in landfill, to a circular economy based on the closed-loop principles of recovery, reuse, repair, and remanufacture, thereby increasing resource productivity.

Unfortunately, to date, most digital technologies seem to boost economic processes and do not yet have a sufficient emphasis on reuse of products and material (i.e., the circular economy). Part of the problem lies in the rapid pace of technological development. Increasing computing power, at cheaper cost, has enabled manufacturers to cram ever more features into devices while maintaining prices and profitability. Coupled with enormous marketing campaigns, the "upgrade era" has materialized to the point where consumers are purchasing new "replacement" products on ever shortening timescales, while old ones are discarded with a very limited degree of recycling. Although some of the products being replaced may be truly obsolete, many offer the same functionality as the new version. It is estimated that in the UK four times as many phones languish unused as are currently in use (Benton et al., 2015), and in Germany over 30% of household appliances disposed of in 2012 were still in working condition. Governments struggle to address these issues as the linear one-way use without recycling has been their modus operandi for the past 200 years. Simple pieces of legislation such as the "right to repair", which is designed to overturn companies' monopoly on repair and to tackle planned obsolescence, seem almost impossible to enact, even in the most liberal democracies. Fortunately, some major technology companies are becoming increasingly aware of the potential problems. For example, Fairphone,[1] a Dutch social enterprise that developed the first modular phone to promote a more circular economy, aims to develop smartphones that are designed and produced with minimal environmental impact. A more modest approach is by Apple, which has developed a disassembly robot for mobile phones (Figure 7).

Moving to a circular economy may go some way to alleviate the loss of jobs brought about by increasing digitalization, as new jobs are created in growing "green industries" (Jensen-Cormier et al., 2018), particularly in the developing world (OECD, 2012).

1 https://www.fairphone.com/en/

Figure 7. Apple has a new iPhone-destroying robot called Daisy that can disassemble 200 phones in an hour. Source: Courtesy of Apple Inc.

4.2 Social Inclusion – Overcoming the Digital Divide

Digital technologies have spread rapidly in much of the world. They can be a powerful influence in helping to overcome social inequalities, but they are also characterized by inequalities themselves. Large disparities in access to, usage of, and skills relevant for digital technologies exist, which are summarized as the "digital divide". Even more importantly, gaps also exist in the broader development benefits from using digital technologies. Digital technologies have often boosted growth, expanded opportunities, and improved service delivery, yet their aggregate impact has fallen short of being inclusive and is thus unevenly distributed.

The digital divide relates to a range of deep inequalities, often relevant at different scales both within countries (between social groups, age groups, genders, urban and rural areas) and across countries. Inequalities pertain to:

- Access to, and use of, digital technologies (including relevant skill sets, education, quality, and affordability of technologies or services);
- Impacts on the economy through productivity gains, changes in industries, job losses, etc. (related to dividends from digital technologies and services);
- Concentration of knowledge, power, and revenue regarding the development and ownership of hardware, software, and data;
- Disparities between technology providers and users (nations, communities, companies, citizens).

Digitalization brings the promise of social, political, and financial inclusion – but this promise can only materialize if the technologies reach those who are currently left behind. The recently published book, *Weapons of Math Destruction* (O'Neil, 2016), warns of the dangers of algorithms and how they essentially contribute to leaving people behind. Patterns of inequalities (in relation to, for example, gender, geography, race, disability, age, and class) will continue to be challenges in the digital era unless they are actively addressed. Future and further digitalization may, if not managed well, exacerbate already present divides; however, if well managed, it can connect people and societies and facilitate inclusion without borders.

On a global level, digital divides are predominantly linked to access. Many of the access divides relate to the physical reality: around half of the world's population still lack Internet access (Figure 8) and a billion do not even have access to electricity, a huge barrier to digitalization. This does not account for discrepancies in reliability, affordability, and the quality/quantity of service use. However, digital technologies, such as the Internet or smart mobile phones, diffuse more rapidly than some basic technologies, such as improved sanitation or electricity (Figure 9). Leapfrogging in developing countries has been mentioned many times,

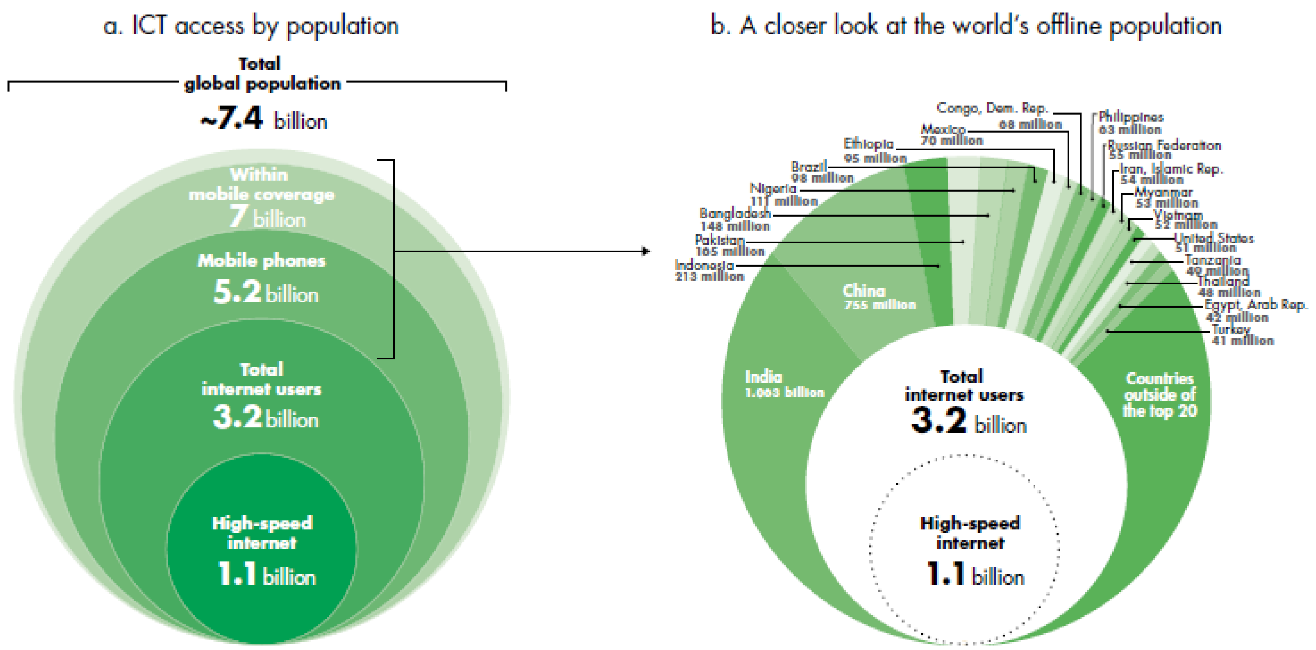

Figure 8. The Internet remains unavailable, inaccessible, and unaffordable to most of the world's population. Note: High-speed Internet (broadband) includes the total number of fixed-line broadband subscriptions (such as DSL, cable modems, fiber optics), and the total number of 4G/LTE mobile subscriptions, minus a correcting factor to allow for those who have both types of access. 4G = fourth generation; DSL = digital subscriber line; ICT = information and communication technology; LTE = long-term evolution. Source: World Bank (2016), CC BY 3.0.

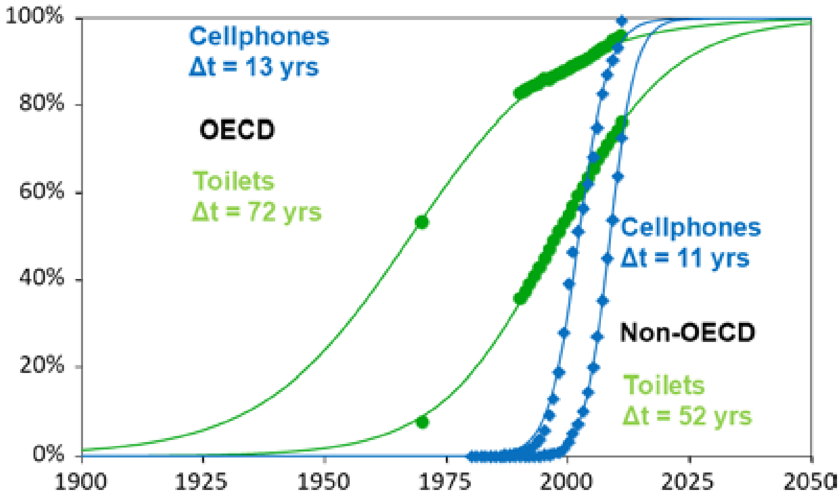

Figure 9. Digital technologies are spreading rapidly in developing countries. Technology diffusion comparison: Diffusion of cell phones vs. toilets for OECD countries (solid) and non-OECD countries (dashed). Data source: World Bank WDI, CC BY. Source: Model fit and graphic courtesy of Arnulf Grubler, IIASA.

as fixed-line telephony never reached as many homes as mobile phones do today.

Digitalization can also bridge divides. A recent study by the World Bank (2016) has shown that Internet access is more evenly spread than income (Figure 10), while economic disparities remain large and pervasive, even across generations (Figure 11).

Internet access can remove the barrier of geographic access, opening up access to information sources in faraway places. However, access to these resources may still be prevented by the lack of electricity access, Internet costs, journal paywalls, language, and other conditions unrelated to the availability of information itself. Open source encyclopedias such as Wikipedia and free courses further ensure the spread of information in the digitalized world. If the current trends of electricity and Internet access continue, the proportion of people with access to the Internet will continue to grow over the next 10 to 15 years to reach almost full coverage around 2030.

Another aspect of digitalization and Internet access is the spread of the use of social media and the changes in social interactions. Social media can function as enablers for social movements to take root. There are, however, downsides of this as social media may drive people to uniformity and limit a healthy diversity of perspectives reaching everyone, creating "echo chambers" in which people only hear information agreeable to their standpoints. The development of echo chambers may harm a well-informed public debate. Social media usage may also reinforce the increase of mental disorders. Is has been shown that limiting social media platform usage decreases loneliness and depression (Hunt et al., 2018).

Internet access can enable information access and provide new avenues and opportunities for doing things differently. A much-used example of how digitalization can enable financial inclusion is the Kenyan mobile phone-based money transfer system M-Pesa.[2] Because M-Pesa works on older cell phones, individuals can easily transfer money without having to go to the bank or have Internet access. Similarly, there are several services in South Africa (e.g., eWallet[3]) which allow people without bank accounts access to finances whether or not they have Internet access. Digital IDs provide identification and related services and rights to people previously excluded; an example is the Aadhaar[4] program in India.

Internet access can also be beneficial for spreading norms and values in line with the notions of human rights, including that everyone should have their basic needs met and the right to human development in line with the capabilities framework (Nussbaum & Sen, 1993). Norms and values can be spread via the Internet, social media, and television. These can provide information about the use of, and access to, family planning utilities, and they can facilitate sexual and reproductive health and rights. New access to media can also challenge traditional gender norms.

There may, however, be conflicts between modern and traditionally held views of society. Such conflicts may harm social inclusion. There is a risk of cultural globalization, often referred to as westernization or Americanization, whereby Western cultures and cultural expressions dominate and kill diversity and local traditions. This may, for example, lead to

2 https://www.mpesa.in/portal/

3 https://www.fnb.co.za/send-money/eWallet.html

4 https://uidai.gov.in/

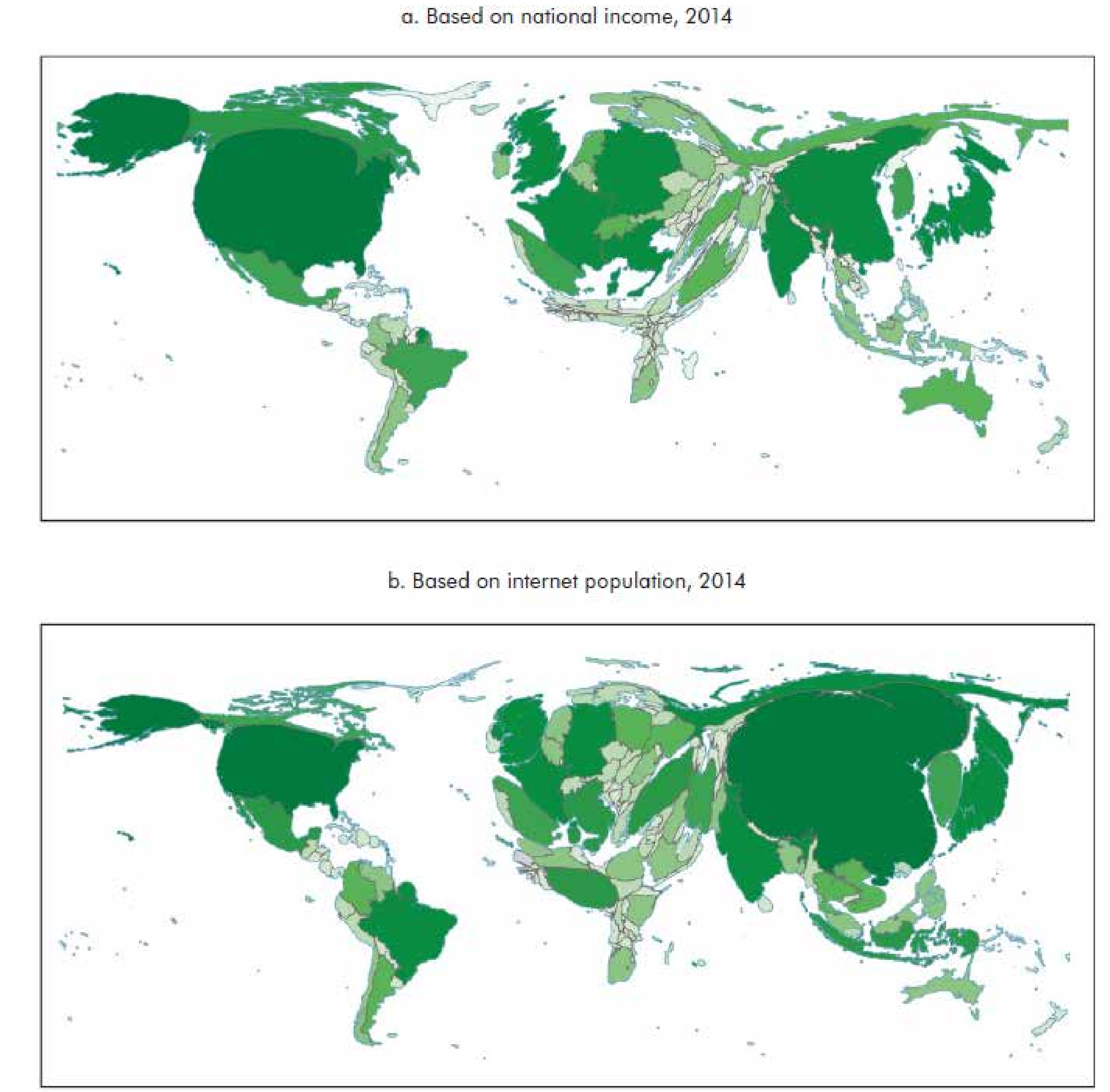

Figure 10. The Internet (panel b) is more evenly spread than income (panel a). Note: Countries' sizes are rescaled in proportion to national income and Internet population. The darker the shade, the higher the national income (panel a; GDP at market exchange rates) and the higher the Internet population (panel b). Source: World Bank (2016), CC BY 3.0.

unhealthy food preferences that are not appropriate to the local conditions, or to destructive consumerism.

Achieving a basic level of literacy and numeracy universally was an objective of the Millennium Development Goals (MDGs). The SDGs move to broader goals in educational attainment, skills, and equal opportunities. The Digital Revolution within contemporary and future society means that (evolving) digital literacy and access to digital technologies are essential. As digital technologies become ever more embedded in everyday life – and increasingly taken for granted by those with relevant technologies, skills and understanding – so the exclusion of the digitally illiterate deepens. Such exclusion is a major policy concern in all countries.

The digital divide reveals a tendency for the most privileged to enhance their advantage and leave others behind. To ensure that individuals, communities, and nations benefit from digital technologies, policies need to be targeted in areas strongly related to education. Policymakers should focus their efforts on ensuring access for all to hardware and software, which will require investment in infrastructure and open source applications.

For digital technologies to benefit everyone everywhere, it is necessary to close the remaining digital divide, especially in Internet access. But greater digital adoption and access will not be enough to generate digital dividends. To get the most out of the Digital Revolution, countries also need to work on the "analog complements". This will involve strengthening regulations and policies so that there is competition among businesses, adapting workers' skills to the demands of the new economy, and ensuring that institutions are accountable. Examples include access to and quality of educational opportunities, investment in the new roles and skill sets of teachers, promotion of

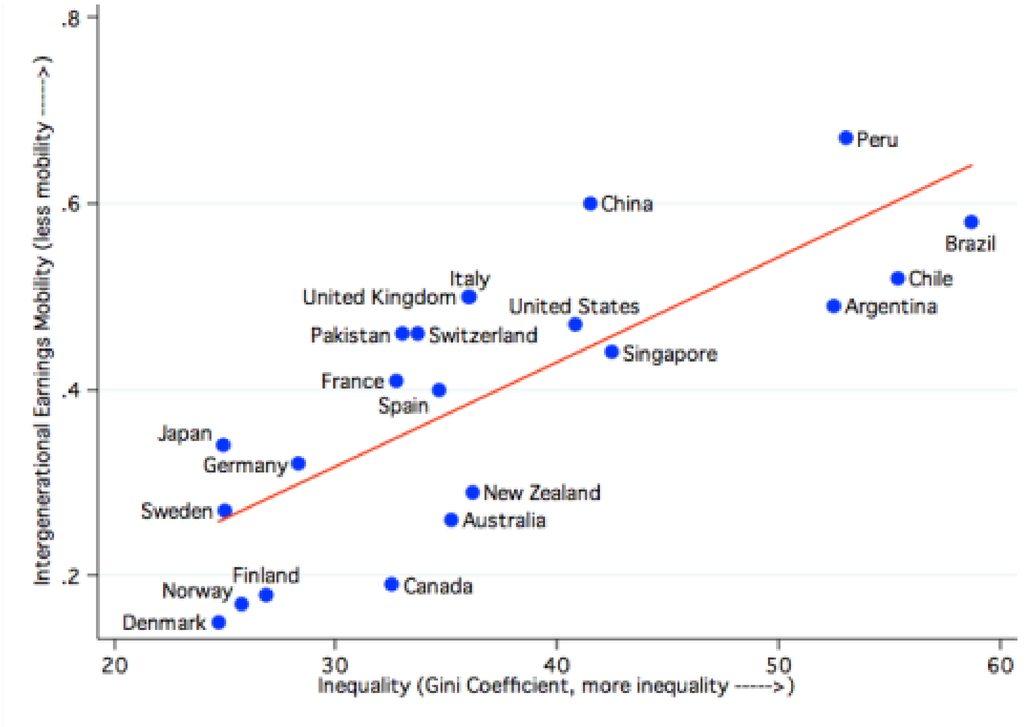

Figure 11. Great Gatsby Curve. Source: Corak (2013).

life-long learning, use of digital technologies to enhance citizenship and support, and the encouragement and direction of research and development of digital technologies.

4.3 Environmentally Oriented Sustainability

The relationship between technology and environmental sustainability has a checkered history. Some argue that the rapid, essentially unchecked, adoption of technology over the last 200 years has led to unprecedented environmental degradation, unsustainable resource extraction, increasing pollution, climate change, and loss of biodiversity and accompanying ecosystem services, to the point where we are rapidly reducing the ability of Earth systems to cope – that is, we are nearing the planetary boundaries. The Anthropocene is typified by rapid technological advancement.

At the same time, advances in technology and digitalization have the potential (as explored in detail below) to drive society toward a sustainable future, but only if this can be done sustainably and within planetary boundaries. For example, electric vehicles offer enormous potential to improve mobility, reduce harmful emissions and pollution, and mitigate climate change, but not if the electricity required to power them comes from unsustainable power generation, such as coal. The almost universal and rapid uptake of digital devices, together with their relatively short half-lives, risks accelerating the depletion of the Earth's resources, particularly of relatively rare resources required in the manufacture of these devices. In addition, digital devices require increases ofor their manufacture and operation, and they contribute to the growing problem of e-waste.

Mobile device penetration has gone from zero to over seven billion[5] (ITU, 2018) in less than 30 years, with an additional 250 million other connected devices (e.g., cars, appliances). This enormous increase in consumerism places additional stresses on the environment. A recent report (The Shift Project, 2018) has estimated that the percentage share of global greenhouse gas (GHG) emissions resulting from digital technologies will rise from 2.5% in 2013 to 4% in 2020 and 8% in 2025, primarily due to increases in energy consumption over this period. However, it has been shown that if new, highly efficient technologies can be used to substitute existing low-efficiency technologies, then the carbon and energy and cost savings could be significant (Grubler et al., 2018).

There is clearly a trade-off between increasing digitalization and environmental sustainability that needs to be carefully managed. Unfortunately, the speed of the Digital Revolution is such that it seems that regulators cannot keep pace. Policies are created and frequently enacted after the fact rather than before. To ensure sustainable management of digitalization,

5 In 2018, there were 107 mobile phone subscriptions per 100 inhabitants worldwide, showing the inequality of distribution (ITU, 2018).

efforts should be made to design and implement new approaches in the governance sphere.

These opposite tendencies of technological change present a paradox: technology is a source of human suffering and environmental damage, yet it is also a potential solution to the challenge of achieving sustainability for all. This is another predicament of the Digital Anthropocene.

4.4 Inclusive Good Governance and Peace

Peace and good, inclusive governance are necessary preconditions for sustainable human development (TWI2050, 2018, chapter 5). However, the digital transformation shapes governance systems around the world and impacts peace. Answers to the question of how political actors can shape digitalization toward a "New Humanism" (WBGU, 2019) and peace are urgently needed. The digital transformation challenges the global and political orders as we know them. It also introduces new forms of warfare, such as cyberwars or drone wars. Still, states and societies need flexible and capable political institutions and systems that address these political and security challenges while at the same time making best use of digital tools to do so. Table 2 summarizes the necessary governance reforms for the transformation to sustainability. The reforms remain the same as those in TWI2050 (2018), in particular the call for (i) flexible but stable institutions, and (ii) multilateral institutions that are capable of governing transnational dynamics. As we will see below, it will be crucial to govern peaceful and human relationships between states, firms, and people.

Digitalization and new technologies present significant opportunities for governments, communities, and the private sector to come together to achieve the SDGs. Policymakers must, however, remember that managing collective goods is at root a political, rather than a technological, task. This is crucial for getting the best out of digitalization. The risks of bringing digital technologies into contested governance spaces are great. Technology is an amplifier of human intent (Toyama, 2011). It tends to magnify existing inequalities and is not a solution to collective problems that are socio-political and political-economic at heart. However, there are many ways that data and technology can be used for good as long as inclusive governance and democratic participation are at the heart of digital endeavors. Technology has

Table 2. Governance reforms needed for the transformation to sustainability. Source: Adapted from TWI2050 (2018).

Problems to solve	Reforms needed
Sustainability transformation as a civilizational challenge	Six normative innovations: 1. Earth-system responsibility 2. global commons perspective – transnational fairness and justice 3. anticipate environmental impacts of decisions for many generations to come 4. learn to shape deep technological change, driven by artificial intelligence, virtual realities, and automated technical systems, toward sustainability 5. create guardrails for "human enhancement", protect people from digital authoritarianism, build social contracts for a "New Humanism" 6. culture of global cooperation and norm diffusion through transnational governance
Digital transformation as a civilizational challenge Flexible but stable institutions needed	Establish governance systems that regulate data control and access, and hold private and public actors accountable for the "New Humanism" Network governance fostering interplay between formal institutions and governance networks
Overcoming institutional, political, and sectorial path dependencies	Building transformative alliances across sectors and public spheres (state, market, and civil society) from local to global
Integrated policymaking across borders and sectors, and SDGs	Polycentric, multiscalar governance and integrated management
Deep transformations require broad public legitimacy	Invest in drivers of motivational change: 1. normative triggers: How can we accept that? 2. demonstrating success 3. attractive future narratives
Dysfunctional and weak international organizations	Reinforce multilateral cooperation; strengthen autonomy of international organizations

politics, reflecting our values back to us at the speed of computing. Bringing inclusive and democratic governance to the implementation of digital services to meet the Agenda 2030 goals can bring significant benefits to humanity.

To begin to assess the role that technology can play in meeting the SDGs, it is crucial to bear in mind that technology is not an ontological artefact that influences global politics beyond the scope of human processes. In his seminal article "Do Artefacts Have Politics?", Langdon Winner (1980) explained how the integration of new technologies into socio-political and political-economic systems is reflexive: the human systems of governance reflect the preferences of the public, and thus the technologies that are selected to support public service provision take on those political features. In some cases, technologies map onto a community's existing internal sociological structures, while in other cases the integration of a new technology into a social or administrative system is dependent on external intervention. In the 21st century, with digitalization relying so heavily on privately owned systems and software, the nature of the organization of the interface between governance, politics, and technology will be crucial for creating systems that benefit both communities and technology providers. Mutual benefits and maintenance of collective goods are far from guaranteed when involving private sector actors in critical social processes, and the use of open source systems is not a silver bullet for solving the tensions between private profits and public benefit. Inclusive, and to some extent democratic, governance is necessary if digital technology is to serve as more than a way for private enterprise to extract value from collective goods. The effective integration of digital technologies into the solutions to massive collective challenges comes with its own complex governance and political challenges.

The distribution of collective goods, whether they are education (Box 3), energy, water, or infrastructure, is an inherently political process. What we hope to achieve with digitalization is increased efficiency in the provision of these goods, and, as an outcome of this efficiency, more equitable access to the best of these collective goods. Digitalization comes with a wrinkle that makes governance of the digital commons even more complex: Technology firms are also competing for contracts and data, which are the lifeblood of their revenue and profit streams. Thus, there is a tension between whether a technology firm is truly committed to supporting access to public goods, or if it is participating in the provision of public goods merely as a way to gain access to the data that underpins a firm's value.

Before attempting to square the challenges associated with public resource distribution through technological means, it is therefore important for policymakers to understand the role of data in the valuation of modern technology firms. Data has inherent value (Akred & Samani, 2018), largely for advertising, and firms like Google and Facebook have maximized the ways that Internet-based technology collects user data. User data is so valuable that there are even arguments that there should be ways to make firms pay users for using their data for revenue generation (Zhu Scott, 2018). This has profound implications for allowing private technology firms to intervene in public processes. When a city collects data on its residents, the data collection is paid for with tax dollars, and those tax dollars represent a fiscal contract between the residents and city government that the data will be used for public benefit. When Google collects residents' data in a proposed smart city, they are responsive to shareholders, and that data must be used to maximize private value – public benefits and efficiencies are not guaranteed. This tension is happening in real time with Google's Sidewalk Lab's proposed Quayside smart city in Toronto, as a lack of transparency and data privacy concerns have led to citizen pushback against the proposal (Canon, 2018; Kofman, 2018).

From a software perspective, the push for open source is positive but must be balanced against the costs to human resources and quality control. Free and open source software (FOSS) has advantages over proprietary packages on the acquisition side: it is free, and the code can be replicated publicly, so there is a level of transparency about what a government is using to manage its computing infrastructure. Linux Foundation (2017) outlines a set of challenges that any organization, including governments, needs to be prepared for when making the switch to a FOSS platform. The biggest challenge is human resources: Do organizations have the necessary software development and quality control competences among their staff to ensure that the software meets the needs of the organization? In many cases this can mean having someone with the technical knowledge to evaluate dozens of interrelated platforms, since a single FOSS implementation could require integrating software from multiple sources.

Technical knowledge feeds into the next challenge governance organizations face with FOSS, which is quality control. Communities of users generally maintain FOSS software; because of this, it is important to make sure that software meets an organization's quality, security, and usability needs. Some FOSS packages are serious professional endeavors, while others are amateur efforts designed to meet someone's specific needs. Finally, organizations will need to fundamentally rethink contracting and acquisition of information technology services because there is no centralized customer service center for FOSS. It offers a number of opportunities for governments who want to implement flexible, distributed digital platforms for meeting different components of the 2030 Agenda, but these opportunities need to be balanced with the political and budgeting changes that come with effective FOSS implementation.

Box 3. Private versus Public Goods in the Education Sector

Education (see 6.1.2) is a good example of a sector where the tension between public good and private benefit exists at multiple levels. Education aims to educate active citizens, to develop skills that can be used in the economy, and to enable social mobility; the first two of these represent collective goods, whereas the third is a private good (Labaree, 1997). Increasingly, the social mobility component of education has come to the fore, making education a commodity that individuals seek as the collective goods of active citizenship and skill building have taken a back seat (ibid.).

With this dynamic in the background, policymakers must be careful to understand how digitalization, far from expanding the collective benefits of education, can magnify the commodification of education. Knowing that self-betterment is a key driver of modern education, where do Massive Open Online Courses (MOOCs) fit into the notion of education as a public good? Firms like Coursera,[1] Udacity,[2] and Khan Academy[3] represent some of the largest MOOC providers, operating in both for-profit and non-profit modes. While these firms provide a wide range of courses, including many backed by world-class universities, there is a risk that they are directly promoting the private good of self-betterment as the primary purpose of education. They do not offer courses on local or national politics, nor do they aim to produce more engaged citizens. For example, the skills courses offered by Udacity are entirely oriented toward the computing and software industries.

Digitalization of education sharpens the utopian vision of access to education resources for everyone, yet this vision runs up against the economy of providing these services for “free”. Universities pay to have their content hosted on Coursera’s platform, and students pay for access to courses on Udacity that prepare them for a specific industry. The social aspects of learning risk being lost, and the firms that provide these platforms do not have a responsibility to students in the way that a tax-funded school system does.

1 https://www.coursera.org/

2 https://eu.udacity.com/

3 https://www.khanacademy.org/

5 Digitalization and Sustainable Development

5.1 A Systems View

The 2030 Agenda is holistic, with deep and complex interactions across the SDGs and their targets. The 17 SDGs are integrated and complementary, and they need to be addressed in unison. A focus on individual or selected SDGs – whether during policy analysis or implementation – comes with the dangers of adverse side effects related to other SDGs or of missing out on potential synergies and resulting multiple co-benefits. A holistic systems perspective helps to prevent lock-ins and mobilizes opportunities to accelerate and leverage the transformation toward sustainable development. The convergence of knowledge, technology, and society must be considered to ensure solutions for the SDGs (Roco & Bainbridge, 2013). It also enables the exploration of multiple possible implementation pathways. Similarly, the Six Transformations are not intended to be viewed as separate domains but rather as parts of a highly interconnected system: changes in one domain will inevitably result in changes, to varying degrees, in all the others. Although not arbitrary designations, the Six Transformations attempt to simplify the complex nature of the sustainability agenda by making it more understandable and tractable.

Similarly, the Digital Revolution should not be viewed as being outside, or separate from, the other five transformations. It is deeply embedded within all of them (as highlighted in the examples that follow), and, as one of the Six Transformations, it is arguably a key driver in achieving a sustainable future for all. However, digitalization is not a single entity or technology; rather, it is a highly interconnected system in itself. It represents the convergence and interplay of many fields, such as computer science, engineering, informatics, mathematics, biotechnology, nanotechnology, and manufacturing. To reap the potential benefits of digitalization for sustainable development will require continued developments across all these domains, as well as in other disciplines, the social sciences foremost among them.

In this chapter, we present a series of vignettes that serve as examples of the opportunities and challenges the Digital Revolution presents across selected elements of this interconnected system. For simplicity, these vignettes are presented under the transformation framework. The selected stories are not intended to be comprehensive, exhaustive, or overly analytical; rather, they provide an overview of some of the dramatic changes expected as a result of digitalization and its impact on the sustainable development agenda. Hopefully, when reading these stories, the deep interconnections between the various topics will become clear, highlighting the need to address the Digital Revolution in a systemic manner. For example, improvements in education brought about by digitalization will have significant impacts on people's health and wellbeing, how and where they live and work, their prosperity, how much energy they consume, their mobility, their consumption patterns, and even their attitudes, behaviors, and social interactions. All of these changes affect how we produce our food, provide services, build infrastructure, and so on. Therefore, it is neither possible nor desirable to think in terms of the impact on education alone – or, indeed, on any other single driver of change.

Although some topics (e.g., poverty) are not covered explicitly, it should be evident from the other topics (e.g., education, health, agriculture) how digital technology impacts the relevant interconnected SDGs.

5.2 Human Capacity & Demography

5.2.1 Health

Technologies have always played an important role in health systems. In particular, imaging technologies, from x-rays and computed tomography scans (formerly known as a computerized axial tomography, CAT) to nuclear-magnetic resonance (NMR) scans, have improved diagnostics and led to a major reduction in invasive procedures. These technologies are rapidly becoming portable and personal; for example, ultrasound technology is available via smartphone, offering huge potential in the developing world (e.g., Butterfly Network[1]). Digital medicine involves new revolutionary technologies and algorithms, combining the fields of traditional medicine, computer science, robotics, and applied mathematics. Recent trends range from new technologies and business models to mobile health, telemedicine, 3D printing, robotic surgery, genetic sequencing, biotechnology and synthetic biology, genetic profiling, personalized medicine, gene therapy, computer-assisted diagnoses, and virtual reality (Figure 12).

With the rapid global uptake of smartphones and fitness trackers, people can easily monitor many aspects of their health in real time. They can count

1 https://www.butterflynetwork.com/

Box 4. Narrative for 2050: Human Capacity & Demography, Education, Health, Aging, Labor Markets, Gender, Inequalities

Premature causes of death decline rapidly for all through the provision of universal preventive and curative medical care. Improvements in health care lead to increased life expectancies which by mid-century are globally comparable to those in the developed world today. Investment in education increases dramatically with a special focus on girls in the developing world, such that enrollment levels are achieved that lead to universal attainment of primary and secondary education levels for girls as well as boys. As knowledge societies spread worldwide, tertiary education includes most people and secondary becomes universal. This contributes to a demographic transition toward slower global population growth, with the result the world's population is less than nine billion by 2050 and will decrease to current levels by the end of the century (Lutz et al., 2018; Wittgenstein Centre for Demography and Global Human Capital, 2018). Slower population growth has led to gradual healthy aging, with one fifth of the population above the age of 65 years in 2050. New employment demand arises in the health, education, research, and social sectors. The Digital Revolution places a significant demand on high educational attainments and skills and offers improved care of the elderly beyond enhanced and universal health care.

steps, track calorific intake and expenditure, monitor heart rate and sugar levels, and even take rudimentary electrocardiograms. This has enabled people to keep track, and take control, of these health parameters, and it has led to an increase in people's motivation to stay fit and healthy. Numerous examples have been reported of how these new mobile technologies have saved lives.

Telemedicine has the potential to reduce inequalities in access to modern medicine and medical practitioners in many parts of the world, particularly in remote communities (Bradford et al., 2016). For example, a "self-service" telehealth clinic was recently opened in a remote outback community (population of 12) in Australia, enabling patients to be seen remotely by a health professional and to have access to routine medicines when doctors and nurses are unavailable (Briggs, 2019). Telemedicine (with, for example, the delivery of medicaments by drones) will help overcome the shortage of qualified health professionals, and reduce travel and waiting times for patients, resulting in large savings for the health system.

Advances are also being made in the incorporation of telehealth technologies in the home. For example, connected health monitoring systems can send real-time information and data about the state of the patient via smartphone, delivering constant updates to their doctor. These can be analyzed and sent back to the patient who has not even left the room. Doctors are even implanting monitors/sensors within hip and knee implants to measure pressure, blood flow, and more, all in real time without any action on the patient's part. Cisco (Cisco Spark and Cisco Extended care services) is building these services in homes (Sprinkle, 2017).

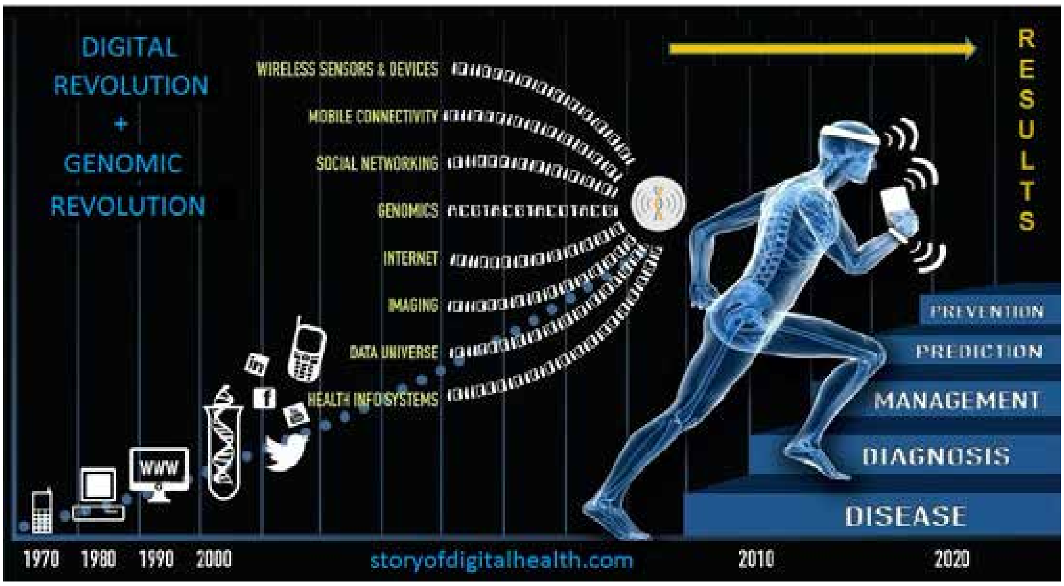

Figure 12. The story of digital health: Technologies comprising the Digital and Genomic Revolutions. Source: Paul Sonnier (https://storyofdigitalhealth.com/).

Cars are already being equipped with mobile phones that can report the degree of injury in case of accident and alert emergency services, which can not only save lives but also improve automotive design to prevent accidents in similar situations in the future. In addition, the high level of "self-awareness" of vehicles through sensors and high-computing power will facilitate accident avoidance and early warning in case of health issues that some passengers might face.

3D printing is rapidly becoming a reality for producing personalized prosthesis, such as artificial joints, limbs, and dental enhancements, at increasingly reduced costs. Advances are also being made in the printing of living tissue and organs. Researchers recently announced the world's first 3D-printed heart using human tissue (Noor et al., 2019). The industry generally assumes that entire organs for surgery will be available in 10 to 20 years. This will essentially overcome rejection complications and virtually eliminate the need for animal experimentation.

Robots are increasingly being used during surgical procedures. At present this involves a surgeon "directing" a robot to perform the surgery, although advances are being made toward fully autonomous surgical robots. In the USA, 90% of prostate surgeries are performed using robots (Navaratnam et al., 2018). An excellent example is robotic-assisted surgery with the da Vinci® Surgical System developed by Intuitive Surgical (Figure 13). The system allows surgeons to perform complex surgical procedures with precision, accuracy, and minimal invasiveness. Robotic-assisted surgery and anesthesia enables surgeons to perform delicate and complex operations with only a few incisions. The system thereby advances and expands the surgeon's capabilities and offers an alternative to open surgery.

Virtual reality will become an essential component of digital medicine. Doctors and medical students are already being taught about virtual objects, and they take part in live surgery via virtual-reality headsets. Nurses learn how to deal with patients in virtual environments. A dentist can train his or her skills on virtual-reality models. Virtual therapies against phobias and paranoia, as well as rehabilitation applications, are already being tested.

Gene therapy offers enormous potential for personalized medicine. Since the elucidation of the structure of DNA in 1953, rapid advances in biotechnology have led to the point where it is now possible to manipulate and edit individual genes. The first human genome took 13 years to sequence at a cost of almost US$3 billion (NIH, 2019). It is now possible to get the same information in under a day at a cost of less than US$1,000 (NIH, 2019). It is becoming increasingly commonplace for a cancer patient's tumor cells to be sequenced to identify specific mutations that can be specifically targeted for individualized treatment. Gene therapy has the potential to eliminate most genetic metabolic diseases. However, it is, of course, accompanied by significant ethical challenges. Genome editing represents one of the most promising areas of biotechnology, with the potential to produce transformative breakthroughs in both human health and agriculture (Biotechnology Inovation Organization, 2019). The US National Academy of Sciences recommends the implementation of safety and ethical regulations as the best strategy to avoid the loss of public trust, and thus to preserve the potential

Figure 13. (Left) A da Vinci Surgical System at Addenbrooke's Treatment Centre during the 2015 Cambridge Science Festival. Source: Cmglee – Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=39154360.
(Right) The surgeon console of a da Vinci Surgical System at Addenbrooke's Treatment Centre during the 2015 Cambridge Science Festival. Source: Cmglee – Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=39437443.

of the technology to benefit humanity (NAS, 2017). The outline proposed by Royal Society (2012) under the concept of "intelligent openness" provides a roadmap for the changes needed to make science and technology more open toward leveraging the involvement of an informed public.

Computer modeling and big data are increasingly used for drug discovery, which, together with advances in synthetic biology, offer the possibility not only of discovering new therapies and pharmaceuticals, but also of making them personalized and cheap to manufacture. Machine learning and artificial intelligence will result in better, personalized disease diagnoses. Computers are already being used in image analysis of x-rays and in biopsy scans for breast and ovarian cancers, with accuracy rates greater than 98% (Griffin et al., 2009). In the near future, doctors will be able to input a patient's symptoms and test results into a computer which will return the most likely diagnosis based on machine learning from large patient data sets. Taken together, these technologies will have a significant impact on the global health system both for patients and for providers. This will undoubtedly lead to better health outcomes and improvements in human wellbeing and quality of life (Collins, 2010; Jackson & Chester, 2015). However, this revolution is not without risk (Antoñanzas et al., 2015) (Box 5).

While universal access to digital technology and data is clearly a prerequisite for the medical benefits from digitalization to materialize, this alone is not sufficient unless people also have the knowledge and skills necessary for understanding basic processes and determinants of health as well as the consequences of health-related behaviors. Otherwise, people provided with health indicators (e.g., heart rate, body mass index, steps taken, blood pressure) may put their health at risk by engaging in biased behaviors (e.g., by undertaking excessive exercise to improve on certain indicators, biasing their nutrition in an unfavorable way, or focusing exclusively on the available indicators and neglecting other aspects of their health) or even in harmful behaviors (e.g., by following "false" information about the effectiveness or risk of certain treatments). There is much evidence that the educated are behaving considerably more effectively in respect to their health (e.g., Avitabile et al., 2011; Hernandez et al., 2018; Lange, 2011). General and health-specific education is also important when it comes to enabling access to and compliance with advanced and typically complex medical treatments such as personalized medicine or robotic surgery (Fiva, et al. 2014; Frankovic & Kuhn, 2019; Glied & Lleras-Muney, 2008; Phelan & Link, 2005). In summary, digitalization may well empower people to improve their health through behavioral changes or access to highly effective treatments; however, it can only act as a lever to the extent that individuals are sufficiently educated.

Access to advanced (personalized) treatments also raises important governance issues. Many such treatments are likely to be very costly in their application or their development. If such treatments are developed or provided through private for-profit companies, there is a need to ensure access to all through universal health insurance or public provision without curbing the incentives for innovation (for some discussion, see Kwon & Jung, 2018). Given that these technologies are predominantly developed within advanced economies, issues of patenting and licensing arise at a global level, just as they have done for advanced pharmaceuticals (e.g., Outterson, 2005).

A prerequisite of digital medicine is that a patient's health records need to be stored and to be accessible across the health system. Therefore, it is not surprising that cyber security is becoming a major challenge with the rapid development and diffusion of digital medicine. There has recently been several data breaches and, unfortunately, the health-care industry was a major target. According to the Identity Theft Resource Center Data Breach Report of 2017, health care is the second biggest in contributing to data breaches, with 334 events in 2017; it has the third highest number of exposed records among industries; and it was hit hardest by hacking, skimming and phishing attacks (ITRC, 2018).

In many cases, patients are now choosing to leave health-care providers that have failed to protect their data, or they have chosen not to have their health records digitized. Of particular concern is the use of a person's health record by third-party external entities to deny people basic services, such as insurance or employment. These issues highlight just how critical compliance and security are to the health-care sector. Quite apart from the risk of illicit access and use of health-related information, people also need to be enabled to assess the consequences and risks involved in voluntary (and legal) sharing of their health-related information. For instance, health insurers are legally entitled to acquire genetic information upon the underwriting of contracts in some countries, which exposes an individual to the risk of obtaining an unfavorable insurance contract or, indeed, no insurance at all. It is therefore important for people to understand at the point of obtaining and collecting information about their own health what risks are involved in the availability of personal health information. This presupposes a certain degree of education and awareness. Further challenges arise in the drawing up of regulations that balance individual, corporate, and governments' interests regarding the access and use of health-care information (Hoy & Ruse, 2005; Miller & Tucker, 2017; Zick et al., 2005).

Box 5. Human Enhancement

In the hugely popular 1970s science fiction action television series *The Six Million Dollar Man* and *The Bionic Woman*, the protagonists, following near fatal injuries, are given superhuman powers in the form of bionic limbs and organs. Perhaps surprisingly, some 40 years later such human enhancement is more akin to science fact than science fiction. Human performance has improved enormously over the last century with unprecedented achievements in sports and knowledge. Digital technologies and their convergence are at a stage when they are already enhancing and augmenting human physical and cognitive capabilities. The first artificial heart pacemaker was implanted into a patient in the late 1950s, and it is estimated that 1.4 million pacemakers will be in operation by 2023 (Statista, 2019). Digital cochlear implants that allow deaf people to hear are routine procedures, and bionic limbs controlled by a patient's own brain are being trialed. New artificial joints, such as hips and knees, contain motion sensors that can monitor performance and detect falls. An "artificial pancreas" that both monitors and controls insulin levels in diabetics will be widely available within the next two years (Bekiari et al., 2018). Neural implants are allowing patients to bypass "conventional" neural pathways and control artificial limbs and peripheral devices by thought alone.

Figure 14. Are human robots the future? Source: Franck V. on Unsplash.

To date, the application of such digital technologies has primarily been to "correct" some form of physical or mental impairment. However, the future use of such artificial organs and limbs will undergo a quantum leap that will lead to new physical enhancements and augmentation, allowing the human life span, which has doubled over the last century, to further increase, perhaps without limits. Some "biohackers" are already experimenting with digital implants that enable them to open doors and cars remotely or to control Internet-of-Things devices (Melendez, 2016).

The major challenge will certainly be cognitive enhancements. Advances in neurotechnology will be a game changer that poses a number of ethical issues (Müller & Rotter, 2017; Prensky, 2009). According to market research firm SharpBrains (2019), there has been a 500% increase in passive neurotechnology patents filed in the USA in recent years. The Internet and mobile applications already provide important enhancements of our cognitive capabilities by providing a kind of external memory and knowledge depository (Massachusetts Institute of Technology's Media Labs already offers a course on cognitive enhancement that explores how future personal digital devices may help with issues such as attention, motivation, behavior change, memory, and emotional regulation). US company NeuroSky[1] has developed a mobile electroencephalography (EEG) headset that passively reads brainwaves and interacts with a number health, education, and gaming applications.

The danger is, of course, a misuse and diffusion of alternative realities that in the future may be fundamentally enhanced by virtual and enhanced realities. The loss of privacy and control of one's data and personality are already a challenge, but they may become huge dangers for democracies and free-thinking people should new bionic and human-enhancement systems fall into the wrong hands or undergo evolution beyond human control. Losing control, and the impossibility of social steering, might be one of the biggest threats posed by the Digital Anthropocene.

Nevertheless, digitalization offers incredible possibilities for freeing humanity from physical toil, and for augmenting and enhancing cognitive and physical capabilities. We are rapidly approaching the age of trans- or post-humanism, in which the demarcation between "human" and "cyborg" (Clynes & Kline, 1960) will increasingly become blurred. The old science fiction dream of machines making machines is a reality today, but machines controlling humans rather than enhancing and augmenting them is a real danger. The future is open, but the direction of change is unknown, so it must become the highest priority for change to be steered toward the Sustainable Anthropocene for all.

1 https://store.neurosky.com/pages/mindwave

5.2.2 Education

Over the coming decades, arguably one of the biggest impacts of digitalization will be felt in the area of education. Beginning with the pioneering use of shortwave radio in the 1950s by Australia's *School of the Air* program to deliver lessons to students living in remote areas (Hanson, 2010), technology has played an important and ever-increasing role in education. Today, the modern classroom, at least in the developed world, sees individual students working in "connected workspaces" with smart whiteboards, individual devices (laptops and tablets), and access to seemingly unlimited sources of information. Ever more higher education institutions livestream lectures and offer entire courses online. The rise of Massive Open Online Courses (MOOCs) has made higher education courses from some of the world's most prestigious institutions accessible to anybody in the world with a reasonable Internet connection, although with caveats (Box 3). Increasingly, virtual reality will allow students to experience field excursions and gain practical experience without ever leaving the classroom or their home (Figure 15). Students have access to "personal" tutors 24 hours a day anywhere in the world through Internet platforms such as chegg.com. Textbooks, school libraries, and even attendance at centralized campuses are in rapid decline.

The Digital Revolution in education will clearly increase access to quality education worldwide in line with the objective of SDG 4 to "ensure inclusive and equitable quality education and promote life-long learning opportunities for all." However, for this to be achieved, the necessary infrastructure of broadband and energy must be concomitantly delivered in the developing world and remote areas. Sustainable future education scenarios reflect such advances (Figure 16). Sustainable education will also provide co-benefits across many of the other 17 SDGs (for review, see Bengtsson et al., 2018), as increasing access to quality education, particularly for girls and women, has been shown to have enormous spin-off benefits for society and human capacity, including increased economic growth (Lutz et al., 2008), improved skills, innovation and increased labor productivity (Cuaresma et al., 2014), reduced income inequality (Abdullah et al., 2015), reductions in population growth (Lutz & KC, 2011), improved nutrition and health outcomes (Lutz & KC, 2011), increased life expectancy (Lutz & Kebede 2018), reduced vulnerability to natural disasters (Muttarak & Lutz, 2014), greater adaptability to climate change (Lutz et al., 2014), promotion of democracy and good governance (Fortunato & Panizza, 2015), and greater environmental awareness and outcomes (UNESCO, 2016).

Figure 15. Virtual reality as educational tool. Source: STEMShare NSW on Unsplash.

Digitalization of education will radically change how course content and curricula are developed and delivered to students. With the growing digital awareness and competence of children, even those of pre-school age, curricula will need to reflect this technologically competent society to ensure students remain engaged in learning. The potential for greater flexibility, standardization, and even globalization of curricula will increase equitability and provide greater choice. No longer will the best outcomes be provided by the "best schools"; there is no reason why an engineer from sub-Saharan Africa will be any less competent than one from the USA or Japan. Students will be able to pick and choose among course subjects on offer and personalize their education to meet their needs and aspirations, learning at their own pace and competencies. Costs for delivering quality education outcomes should be drastically reduced as expensive infrastructure will no longer be required. It is estimated that e-learning alone could result in cost savings of US$1.2 billion per year by 2030 due to a decrease in spending by students (GeSI & Accenture, 2015). Technologies such as telepresence will enable students to participate in classes from home or elsewhere. Collaborative learning among students across the globe will become increasingly commonplace, increasing students' exposure to different cultures and societies. Platforms such as Microsoft's Skype in the Classroom,[2] a free online education community that already reaches more than 1.5 million teachers in 256 countries and 66 languages, with an active 800,000 teachers each month offering live classroom-to-classroom connections, guest speakers, lessons, and virtual field trips.

The impact on teachers will be profound; they will require a radically different skill set to be able to deliver engaging "lessons" via new technologies. There are approximately 80 million teachers worldwide today (Roser, 2019), many of whom have no formal pedagogical training, and the vast majority have no experience or expertise in information and communication technologies (ICT). To realize the

2 www.skypeintheclassroom.com

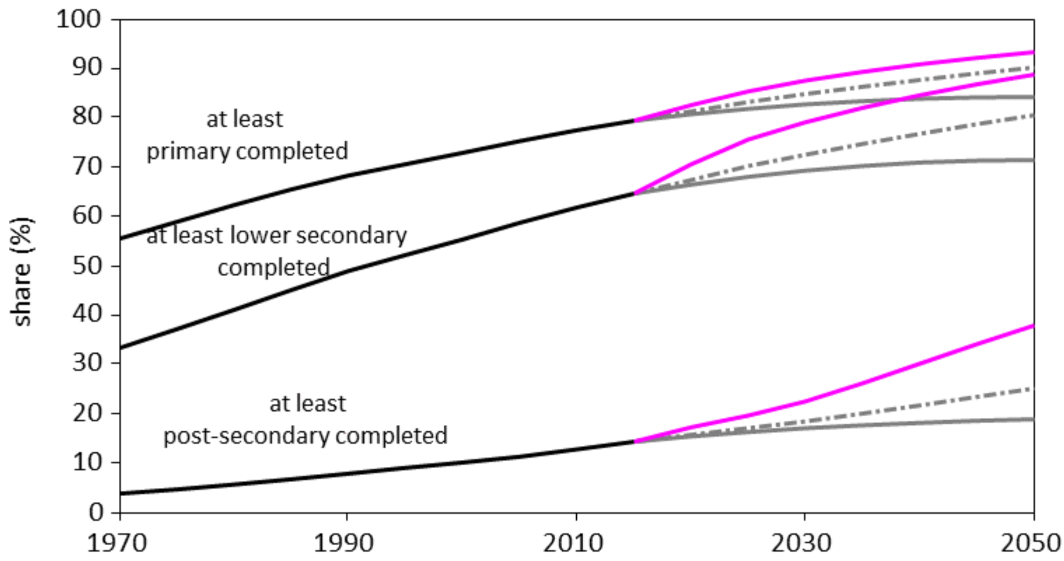

Figure 16. About 80% of the global population over the age of 15 have at least primary education, up from just over 56% in 1970 and 43% in 1950. Three SSP projections are shown: SSP1 is an ambitious pathway and a proxy for a sustainable development pathway (SDP). SSP2 is the trend scenario. In SSP1 and SSP2, the historical trend continues toward almost universal primary education, but the SDP calls for universal secondary education. SSP3 portrays little improvement. The share of the world's population over 15 years of age with at least a secondary education attainment has doubled from some 30% to 60%. SSP1 portrays a significant acceleration reaching over 85% by mid-century. SSP3 portrays a deterioration leading to higher birth rates and global population. Most importantly, post-secondary attainment increases in SSP1 and nearly stagnates in SSP3. Even in SSP1, the mid-century level is just over 30% and not that much different from secondary education attainment in 1970. This is a huge challenge for knowledge societies in times of digitalization. SDP would definitely need a higher educational attainment if no one is to be left behind. Source: Data from Wittgenstein Centre for Demography and Global Human Capital (2018) and Lutz et al. (2018).

potential of the continuing digitalization of education, it is imperative that students and teachers improve their levels of computer literacy.

The increasing digitalization of education will also impact the structure of our cities and social interactions. As education is increasingly delivered remotely so that students learn from home, either individually or via "virtual classrooms", the need for centralized campuses and associated infrastructure will diminish. Transport needs and patterns will change with an estimated saving of 5 billion liters of fuel and mitigation of 0.1 $GtCO_{2e}$ (one billion tons of carbon dioxide equivalent) per year (GeSI & Accenture, 2015). However, the loss of neighborhood schools and "college towns" may impact the sense of community, increasing isolation among students through a lack of face-to-face personal interaction. This may not be a problem for the new digital generation for which most social interaction is online through social media. Unfortunately, this will not reduce bullying, peer pressure, or social exclusion, as these will simply transfer from the physical world to cyberspace where it is more persistent and anonymous, as is becoming increasingly evident today. More opportunities for physical social interaction will need to be provided at the community level to reflect cultural habits, such as through sport or other activities. "Schools" may become community-based shared learning spaces where students interact to share learning experiences.

It is estimated that over 264 million school-aged children are not receiving education, with most of these in Africa (UNESCO, 2017). Globally, almost 70 million teachers will need to be recruited by 2030 to achieve SDG 4, with 17 million of them required in sub-Saharan Africa based on existing methods of delivering education (UNESCO, 2017). Technological advances in the delivery of classes may dramatically reduce the number of new teachers required, thus allowing investment in improved delivery infrastructure. Providing access to education through technology will prove pivotal in the developing world, where access to schools and quality teachers is particularly problematic. Providing situations where children can learn in their own homes in their own time overcomes the problems of having children attend school during prescribed times at prescribed places, resulting in less interference in daily routines and reduced costs. This will require the necessary infrastructure investments to ensure adequate and reliable high-speed broadband Internet (>50 Mbits per second) and access to electricity.

Box 6. Digital Games in Education for a Sustainability Transformation

Games, whether digital or analog, are structured experiences for playing. Digitalization is advancing games through a quantum leap in creativity of virtual spaces for players. Play is a critical component of learning and inspiration at all ages, not only for its intrinsic motivation of fun, but also for allowing experimentation with less risk and fear of failure. Games provide opportunities to introduce crucial information and concepts for sustainability in non-didactic, developmentally and culturally appropriate ways (Vervoort, 2019), and they can also serve as valuable boundary objects to facilitate dialogue among actors with diverse levels of power, knowledge, and resources in conflict situations (Li et al., 2015). Narrative-driven role-playing games can also be designed to engage players and develop awareness of and empathy with others living in very different contexts and cultures (Mendler de Suarez et al., 2012). Games can become a bridge between, on the one hand, the social affordances of personal presence and face-to-face contact, and, on the other, digital representations as avatars. Playing the game may then help develop a sense of the kinship of interdependence among people and with the environment. There are at least three parallel and complementary strands of digital games:

1. In one strand, games are platforms for experimentation with scenarios that are tuned to a certain subset of parameters critical to the functioning and dynamics of the scenario; that is, they are safe, experimental spaces for (often technocratic) problem solving. This type of experimentation is a fertile ground for collecting and analyzing data on decision making, similar to decision theaters. This is usually most effective if the users (e.g., policymakers, planners, and engineers) come to the experimentation with experience and questions.

2. The second strand consists of games or exhibition pieces designed primarily to engage non-experts and experts alike with memorable, easily accessible experiences that stimulate curiosity and facilitate engagement with a very limited set of core ideas about aspects of sustainable social-ecological systems. In this approach, the model behind the game is intentionally very simple and focuses both on illuminating the few ideas essential for a basic understanding and on stimulating questions and interest. This can be done in dynamic, surprising (often cognitively dissonant), and multisensory memorable ways. The game or exhibit, which could be purely virtual, purely physical, or mixed reality, is an environment that quickly engages and inspires users as they encounter instantiations of core ideas in ways that are readily graspable. On an elementary level of content, it can also function as a problem-solving playground and as a boundary object for stimulating inquiry and dialogue. Games exist that allow coupling of virtual or mixed reality landscapes between different locations; such games engage people in different contexts and locations in open dialogue on specific aspects of sustainability and on the decision-making process in complex socioecological systems. Two examples of mixed reality games are shown in Figure 17 (Kreyon City) and Figure 18 (Energy Transition Game).

3. A sustainability game could engage many people over an extended time in a massive multiplayer online role-playing game (MMORG). It would be a narrative-driven role-playing adventure game related to the urgent and critical challenges of transforming societies at multiple scales and governance levels toward more

Figure 17. Kreyon City augmented reality game prototype, Rome 2017. Source: Ilan Chabay (2015).

Figure 18. Baden-Württemberg Stiftung “Expedition N” traveling exhibition on the energy transition, designed by Ilan Chabay and Ortwin Renn, and visited by 700,000 people from 2010 to 2018. Source: Ilan Chabay (2017).

sustainable pathways. Players would endeavor to achieve futures appropriate to local and regional contexts and cultures. It would be based on a large number of stories, some professionally written and others crowd sourced, from many different sources, contexts, and cultures. The stories would be woven together in a vast landscape. Successful completion of the separate quests in the stories would require learning (in easily digestible chunks) and using local knowledge and norms. The player can use the increasing knowledge, reputation, and resources gained in quests to influence and impact his or her game-world encounters. The idea takes much from MMORG “dungeons and dragons” games, but with real-world political, economic, and social challenges that would need to be addressed by negotiation and problem solving. Players would have to acquire resources, reputation, and influence, rather than increasingly powerful swords and sorcery. Individual players could freely navigate in the virtual landscape, while also being part of a large, changing, and diverse group of players continually acting in local stories, accumulating resources, and building supportive social movements to influence a transformation to sustainable futures in the game world. Players could also work on virtual construction efforts to build installations or facilities (e.g., distributed renewable energy, sanitation, food production). A major challenge in developing the game would be to create an overarching architecture that weaves the separate strands of the stories into a coherent fabric leading toward global sustainability (i.e., a virtual representation of the daunting challenge of dealing with the conflicting interactions and trade-offs in the SDGs). The player enters the game without necessarily having any knowledge of the relationship between the strands or the underlying narrative of social movements toward sustainable futures in multiple contexts and cultures. The overarching architecture only slowly becomes apparent during the pursuit of the many possible story quests and dialogues with other human avatars and non-player characters. Most players would not initially become involved in the game for the purpose of learning about the complex challenges of global change. Nonetheless, raising awareness of and interest in these challenges and the need for sustainability would be the intended outcomes of engaging players over an extended period of time.

To take advantage of the enormous benefits offered by this new education revolution, policymakers need to ensure that all students and institutions have equitable access to these new technologies, particularly in the developing world, where advances in access to education will arguably have the greatest impact. The prospect of only the wealthiest schools and students able to access this transformation must be avoided at all costs. Education can be the great "social equalizer" with the right policy frameworks and investments. Internet access can remove the barrier of geographic access, opening up information sources in faraway places. However, access to these resources may still be prevented by limited access to electricity and the Internet, the costs of the Internet, journal paywalls, and other conditions unrelated to the availability of information itself. Open source encyclopedias such as Wikipedia[3] and free courses further ensure the spread of information in the digitalized world.

The Digital Revolution could also provide new means of public engagement and participation in policy design aimed at guidance and regulation of new technologies (Box 6). Virtual and augmented reality and games are increasingly being used in scenario-building processes, improving our cognitive capacity to understand not only the implications of decisions in complex social-ecological systems, but also the multiple perspectives that guide better decisions. This can be a powerful tool for supporting transformation processes. The power of virtual reality to bridge between groups and tell narratives for audiences that otherwise would have been difficult to reach has been shown by, for example, Voices of the favela.[4] This interactive virtual reality experience enabled local inhabitants to talk about their lives in the favela, with their presentations reaching international experts at high-level events in other countries in Latin America and Europe. A well-informed and educated public could facilitate the adoption of new technologies with key roles in the transformation toward sustainability.

5.2.3 Gender Equality and Empowerment

"Achiev[ing] gender equality and empower[ing] all women and girls" (SDG 5) will support overall development. Any progress in the empowerment of women, specifically facilitated through the Digital Revolution, impacts the other five Fundamental Transformations and 17 SDGs. For example, if we were to improve women's access to sexual and reproductive health, rights, and services, this would also reduce maternal mortality, help end communicable diseases such as HIV and AIDS, and slow population growth (SDG 3). When women and girls have autonomy and relevant information conducive to their health, there are positive effects on education (SDG 4), sanitation and hygiene (SDG 6), and employment (SDG 8). Women and girls are most prone to poverty (SDG 1), hunger (SDG 2), lack of clean energy access (SDG 7), and climate impacts (SDG 13).

Women and girls face barriers to digital inclusion that reflect the gender inequality in the physical world in access to education, careers, and opportunities (Figure 19). Technology can be an enabler of inclusion, but if the environment (economic, political, social) is still discriminatory, women and girls may not be better off. The public sector should lead the way with suitable policies. The private sector (e.g., information and telecommunication companies, banks, health providers) also has a responsibility – as well as a business interest, given the size of the untapped market – in creating better digital products, services, and opportunities specifically targeted to, and addressing, women's constraints, needs, and ambitions. The private sector must help create an enabling environment for women's and girls' empowerment.

For digitalization to become a true enabler of women's empowerment, institutes and public offices must supplement efforts to reduce underlying systemic inequalities, particularly in four areas: (i) in educating girls equally in digital technology so that they have equal access to a digital career (Outlay et al., 2017); (ii) in providing safe spaces accessible to girls and women (De Pauw, 2011); (iii) in teaching awareness of and protecting girls and women from digital violence, such as online harassment (Livingstone & Bulger, 2014); and (iv) encouraging women to become designers and creators of technology (e.g., mobile financial technology) that could be better targeted at improving their own lives, especially for those suffering abject poverty (Plan International, 2018). Again, the private sector plays a crucial role in designing, developing, and offering products and services that enable gender equality. Although many of these initiatives, at first glance, focus on women and girls, men and boys have crucial roles to play in creating more equitable societies.

The current discourse on the Digital Revolution and gender often focuses on inequalities or gaps relating to access to, usage of, or skills needed for novel technologies. The Digital Revolution provides a plethora of opportunities to empower women. TWI2050 is going beyond the dominating discourse on "digital gender divide and gender skill gap", which reflects the extensive gender-related inequalities that currently exist (Hilbert, 2011). In line with the SDGs, TWI2050 envisions a world of equal opportunities. This translates to overcoming existing inequalities in education, health, economy, rights, and participation.

With regards to education, the contribution of digitalization for women's empowerment relates to (i) technologies as a means of increasing the access to

3 www.wikipedia.com

4 https://scenethere.com/home/voices-of-the-favela/

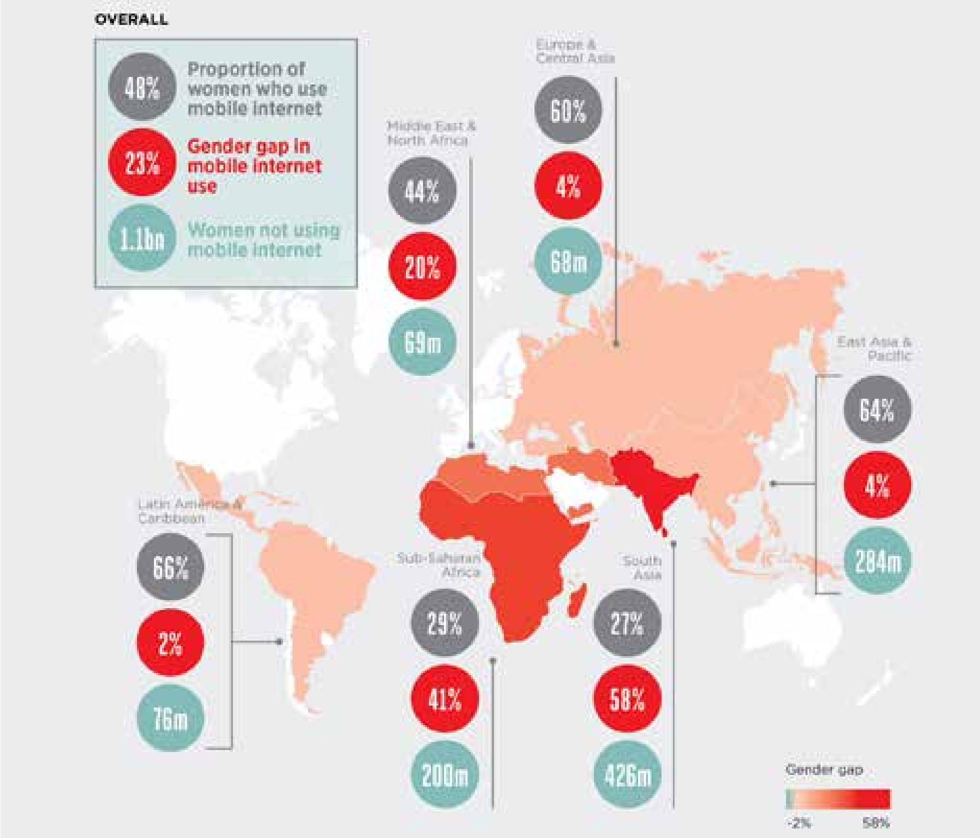

Figure 19. Gender gap in mobile Internet use in low- and middle-income countries, by region. Base: total population. Source: GSMA (2019).

information and high-quality education, and (ii) relevant education for the Digital Revolution (see 5.2.2). In both, there lies a chance of empowering women. Applying new technologies to formal and informal learning can improve access to education in remote areas through online courses. Such distance education will support and enhance the training of women and girls who are not participating in formal education. Another aspect of empowerment is related to the skill sets necessary for the Digital Revolution. Providing women with relevant training strengthens their employability and financial and social independence. There are several examples of such initiatives, such as Change is Made with Code,[5] CodersTrust,[6] or GirlsGoIT.[7]

As with education, digitalization can spur improvements in health (see 5.2.1), particularly in remote areas, by providing information and (mobile) health services targeted at women. While digital technologies can be supportive, policies need to allow for the equal, accessible, and full dissemination of information relating to sexual and reproductive health. Such information and services will include sexual and reproductive rights, which are at the heart of gender empowerment and closely related to fertility rates. Feroz et al. (2017) provide examples of pregnant women receiving regular advice and reminders about pregnancy care and scheduled antenatal visits through their mobile phones in Ghana, Tanzania, and other African countries. Reproductive technologies (such as period tracking apps, in vitro fertilization, and egg-freezing) enable women to take control of their fertility, thereby allowing them to choose if and when to have children. This has direct implications for their ongoing health, education, and employment, as well as for overall population growth. Women, especially pregnant women, are underrepresented as patients in medical research. Increasing the collection and availability of data on gender and sex differences in health services, treatment, and products may improve research and the creation of products and services for women.

The Digital Revolution enhances women's economic empowerment by streamlining production in, and management of, small to medium-sized enterprises, and by creating business and employment opportunities for women as owners or managers of information and communication projects. This can lead to greater economic independence, increased self-esteem, greater respect from others, and more decision-making power within the household. For example, the digital space in conflict-affected countries can be much safer than the workplace in more traditional jobs. The same applies

5 https://www.madewithcode.com/projects/change

6 https://www.coderstrust.com/

7 https://girlsgoit.org/

for women as customers of products and services. Yet, the Digital Revolution and its impacts on the job market also impact women. According to a recent study on the US labor market, although women make up only 47% of the labor force, they perform 58% of the jobs at highest risk because of automation (Hegewisch et al., 2019). This could hamper women's economic advancement. Digital financial services, on the other hand, accelerate financial inclusion. They offer a solution to the gender gap in account ownership, and they increase the volume and value of transactions in formal financial activities (e.g., digital platforms enable crowdfunding for female entrepreneurs). With their financial power often lagging behind men's, women are using their accounts less and have less experience with and trust in traditional financial institutions. Digital services might help overcome these obstacles.

In developing countries, one in two women lack an official identity and women are 50% more likely than men to not have an official identification (ID4D, 2019). Digital technologies and e-governance can facilitate the provision of identities, with their related benefits and access to public and social services (e.g., India's Aahar program[8]). Official identities also bring citizen rights, empowering women to participate in politics and elections. Digital technologies are already being deployed to advance women's rights, and we can build on these developments. Examples include mobile phone apps that allows users to report unsafe spaces (e.g., data collection, safety buttons, helplines) and tools that provide access to relevant information (e.g., domestic violence laws, women's rights, support contacts and groups). Apps can enhance women's networking for business purposes and social organizing, strengthen women's participation in the political process, support the work of female officials, and increase women's access to government and its services (e.g., social payments, rations, pensions).

Digital technologies (e.g., online petitioning and social media campaigning) facilitate the establishment of alternative organizations such as non-governmental organizations (NGOs) to address issues that are not facilitated by traditional avenues. This helps to bring neglected issues (including social taboos like female genital mutilation) into the public arena. The most prominent example has probably been the #MeToo movement against sexual harassment and assault. Digital technologies also help overcome social norms that limit freedom to form associations, participate in formal governance structures, and access public information. They can support the voices of marginalized women. Women can use digital technologies to express themselves publicly, access uncensored information, and form virtual networks, including for campaign purposes.

At the same time, technologies can also be used to control women. For example, in line with local laws and practices, an app exists in Saudi Arabia (Absher) that enables male guardians to track the whereabouts of their female dependents. Although it has been argued that this defies women empowerment, it has also been suggested that the app has increased women's mobility (Bennet, 2019): previously men would just prevent women from leaving the home, but the app makes men more comfortable with women traveling because they know where they are. The issues of data protection and surveillance are of relevance to any of the above-mentioned opportunities offered by digital technologies in relation to gender empowerment. This is not unique to technologies supporting networking and information flow in support of women's rights. It lies in the hands of policymakers to provide an enabling regulatory framework.

5.3 Consumption & Production

The Digital Revolution offers huge potential to make accessible many services in a much more resource-efficient manner (Figure 20).

The largest transformative impacts of digitalization on consumption and production arise from two trends:

1. (Near) zero marginal costs of transactions, that is, an additional unit of consumption (e.g., a video or music streaming and download) can be provided at practically zero cost, thus increasing affordability

8 https://uidai.gov.in/

Box 7. Narrative for 2050: Consumption & Production, Resource Use, Circular Economy, Sufficiency, Pollution

By 2050, the consumption and production of goods and services has moved toward a sustainable pattern. Consumption patterns are driven by changes in technology and behavior, and they are based on a sense of shared responsibility. There is predominant demand for the sustainable use of resources with reduced waste, pollution, and environmental degradation. On the production side, industry is highly automated and organized by a mixture of hubs and distributed elements. In the transition period, this can be facilitated by, for example, additive (3D) manufacturing. Production systems are more localized and self-sufficient, and operate, to a large extent, circularly with full recycling and reuse. Large cost reductions, and changes in regulations and behavior, lead to massive improvements in efficiency and uptake of zero-carbon energy systems.

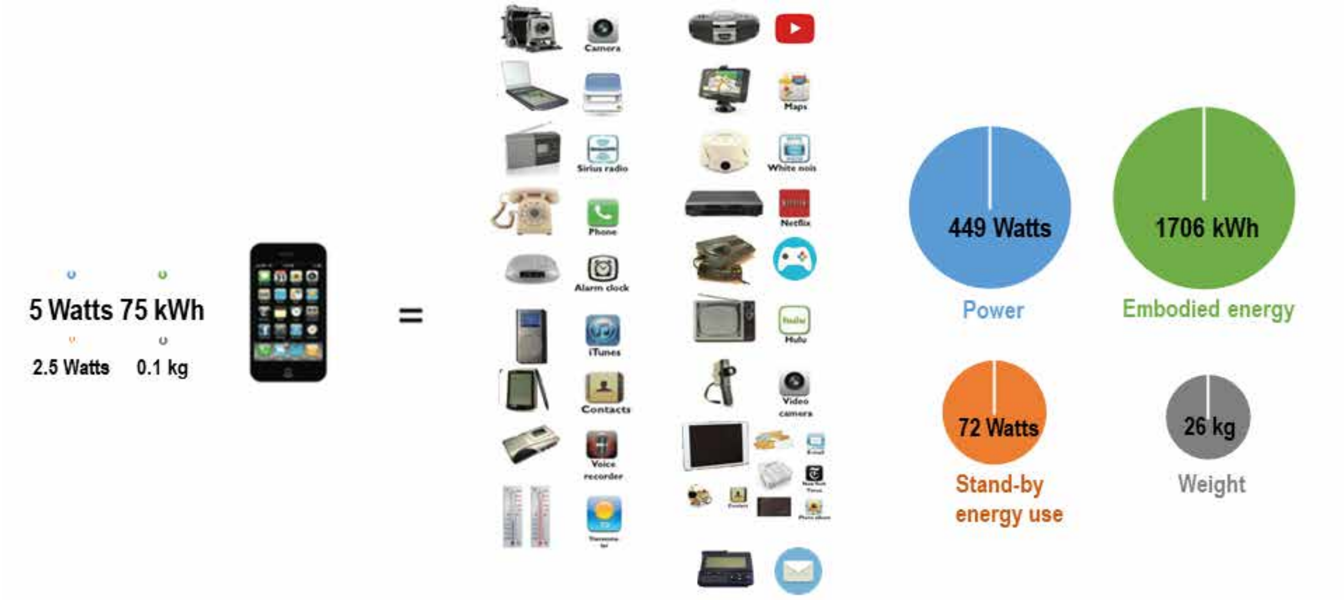

Figure 20. The rapid progress of information and telecommunication technologies could be an indication of the path-breaking potential of next-generation digital technologies and their clustering in new activities and associated behaviors. A smartphone needs between 2.2 Watts in standby to some 5 Watts in use, while the numerous devices portrayed in the figure that it replaces need up to a hundred times more power. There is about a factor 25 reduction of embedded energy required to produce the devices and a proportional reduction in emissions. Bundling of services from various devices in the smartphone can be regarded as an example of the power of the Digital Revolution and its huge potential to increase resource efficiencies through new technologies and behaviors. Source: Nuno Bento, based on data in Grubler et al. (2018) and visualization of Tupy (2012).

for poorer segments of society. Hence, there is interest in substituting current dominant, resource-intensive, physical products and services with digital, "virtual" services as the main element of a strategy toward "dematerialization".

2. The possibility of matching supply and demand in real time through digital coordination platforms offers vast potential for better asset utilization and improved quality of service. This is, in essence, the underlying principle of the "sharing economy" in which the traditional model of service provision is shifted from "ownership" to "usership" of devices that provide consumer services (e.g., cars in ride-sharing services). "Just-in-time" service provision models can also make traditional differentiation between, for example, "public" (large volume, low cost, schedule-based, fixed access and delivery stations) and "private" (low volume, high cost, flexible timing and delivery points) transport increasingly blurred if not obsolete.

The Digital Revolution may be critical for reducing energy and material needs through substitution of "real" services by virtual or digitalized services. Examples of such services are the rapid adoption of virtual communication, meeting services, and tele-conferencing, which have the potential to replace a large fraction of current fuel consumption for long-distance and carbon-intensive business travel (worldwide, one of the fastest growing energy services).

As the experience of digitalized services improves, the services foster increasing use of leisure time for dematerialized and digital entertainment services that range from globally connected computer games to home entertainment services and the creation of virtual reality and society. These activities may substitute many of the current energy-intensive recreational activities, thus contributing to the transformation toward virtual consumption patterns.

The dematerialization potential of virtual consumption is vast, and there are countless possible virtual services, but the widespread adoption of such services may also imply fundamental societal risks. If not managed appropriately, digitalization may lead to power accumulation through centralized data control, increasing the risk of information control and mass manipulation.

The positive impacts of digitalization on the SDGs can be summarized as follows: better and lower cost services improve access and affordability and hence contribute toward reduction of poverty and inequality. Better asset utilization and virtualization increase resource efficiency and can reduce the resource and ecological footprint of human activities, thus positively contributing to a range of SDGs.

Potential negative effects can be grouped into four clusters:

1. Lack of access to digital infrastructure and services compounds the negative impacts of the digital divide, potentially opening up a digital consumption divide. For example, someone who does not own a smartphone could no longer use public transport options organized under a pervasive shared mobility model.
2. Big data applications centered on private consumption and services raise data privacy concerns and present risks of social control by governments and/or large multinational firms. Also, the fundamental nature of network externalities (benefits grow exponentially with the degree of interconnectedness and information sharing) almost automatically lead to natural monopolies.
3. Cost reductions in services could lead to "take-back" (or economic "rebound") effects in which cost savings lead to further increases in the same or substitute demands. For example, cost reductions from shared mobility models for urban commuting to work could lead to increased demands for (long-distance) recreational travel trips on weekends and during holidays.
4. Negative impacts on employment: Better asset utilization in a sharing economy and increasing virtualization, despite reducing resource use and waste, will impact manufacturing through lower demand for devices, vehicles, and physical goods, and hence negatively impact employment. Moreover, increasing digitalization of service provision, such as autonomous vehicles in public transport fleets, reduces the need for human labor, again negatively impacting employment. Concerns are also voiced that continued digitalization in manufacturing could render the traditional comparative advantage of emerging economies in manufacturing (lower labor costs) increasingly obsolete. This could lead to a relocation of industrial and manufacturing activities back to industrialized countries, or it could create an additional entry barrier for resource-based economies that currently benefit from the international division of labor in their efforts to industrialize.

Neither positive nor negative impacts of digitalization on consumption and production are preordained. Public policy is instrumental, particularly in the early formative phase of the development of new technologies and business models, in terms of regulating standards, data access and privacy, monopolies/competition, and, above all, infrastructure development and assuring equitable access.

5.3.1 Additive Manufacturing

Additive manufacturing (AM, also known as 3D printing) was initially seen as a process for concept modeling and rapid prototyping. Being able to "print" weird and wonderful projects has captured the public's imagination. The flexibility in design and physical properties not previously possible mean that there's a range of practical applications and uses (SPI Lasers, 2019). During the last decade, additive manufacturing has expanded to include applications in many areas of our lives. From prototyping and tooling to direct part manufacturing in industrial sectors such as architecture, pharmaceuticals, dentistry, aerospace, vehicles, furniture, and jewelry, new and innovative applications are constantly being developed. In addition, additive manufacturing has revolutionized the design and manufacturing – from consumer goods produced in small batches to large-scale manufacture (Metal AM, 2019). AM has several advantages over conventional manufacturing, including reductions in lead time, reduction of scrap materials, lower inventory costs, less manufacturing complexity, reduced floor space, and the ability to deliver manufactured pieces with complex shapes and geometries. It can yield significant energy and resource savings (IEA, 2017). The applications are vast, and they include exceedingly concerning developments: such as guns that can be printed at home, and it may be even possible one day to print weapons of mass destruction (Metal AM, 2019).

Additive manufacturing uses computer-aided-design (CAD) software or 3D-object scanners to control hardware that deposits material, layer upon layer, with exceedingly high precision. Other advantages are the extensive flexibility of printing directly from a CAD model without the need for any additional tools. This results in the ability to produce complex geometric designs. An example of applications that tap the full potential of additive manufacturing precision and flexibility are dental restorations (see 5.2.1). Already, 3D printers produce everything from prosthetic hands, heart valves, and engine parts, to basketball shoes and fancy chocolates.

Another high-value application of additive manufacturing is in aerospace. The CFM (a joint venture between GE Aviation and Safran Aircraft Engines) LEAP jet engine[9] is an epiphany of disruption. It uses AM to achieve huge improvements in performance and reduction of materials use. For example, the nozzle turbine is 25% lighter and five times more durable than conventionally manufactured parts. It was essentially impossible to produce the nozzle by conventional manufacturing (Kellner, 2017). As a result, it is hardly surprising that other organizations, like Aerojet Rocketdyne and the Chinese People's Liberation Army, are already using additive manufacturing to print sophisticated metal parts for jet engines, rocket propulsion systems, and fighter aircraft (Kaelin, 2013; Kellner, 2017; Zaleski, 2015). The impacts of selected additive manufacturing lightweight metallic manufacturing of components in

9 https://www.cfmaeroengines.com/engines/leap/

the US aircraft fleet are truly disruptive. Under different adoption scenarios to 2050, 9% to 17% of total typical aircraft mass could be replaced by lighter additive manufacturing components. If fully adopted by 2050, this could, in relation to the US aircraft fleet, lead to annual reductions of metal demand by nearly 20,000 tons and of overall fuel use by up to 6.4% (IEA, 2017).

Like many disruptive technologies, however, additive manufacturing has a dark side. The case in point here is 3D-printed guns (Figure 21). Most (in) famous is the Liberator gun with parts that can, in principle, be printed at home with low-cost printers (Greenberg, 2013). One can simply print a gun and fire away. The only non-plastic components of the weapon are the firing pin (a standard metal nail) and a piece of steel, weighing less than 200 grams, whose function is to make the gun detectable by a metal detector. This part can be removed if the gun is intended for illegal purposes. Also, the guns do not have serial numbers, making them, to all intents and purposes, “ghost guns”. Police are concerned that plastic guns allow evidence to be more easily destroyed than is the case with conventional guns. At the same time, however, printed guns may be more dangerous for their users than for those targeted. Ironically, the potential threat level of printed guns could be much higher in places with strict gun control.

An even greater and potentially cataclysmic threat is that additive manufacturing could challenge major control mechanisms for inhibiting nuclear proliferation. Additive manufacturing will make it easier for countries to acquire nuclear weapons, providing a way to print pieces of the nuclear jigsaw puzzle indigenously before anyone notices and making it more difficult for the international community to detect and stop them. If building the bomb is like solving a giant jigsaw puzzle, one of the hardest parts is simply getting all the necessary pieces (Kroenig, 2010). Attempts to buy or build these items – such as the components of a gas centrifuge – are beset with obstacles and set off alarm bells that alert the international community to the existence of a covert weapons program. However, additive manufacturing and the right digital build files would enable a country or a clandestine organization to print many of the specialized components for a nuclear program quickly, with little technical skill, and at low cost. Moreover, hiding such a program would be much easier than under traditional manufacturing methods, rendering obsolete many of the international community’s tools for spotting illicit nuclear activity. Fortunately, the proliferation potential of additive manufacturing has not yet fully materialized.

As with any technological advance, new possibilities come with new perils. Because of the digital nature of additive manufacturing, hackers could infiltrate digital blueprints, resulting in a new kind of threat: cyber sabotage in the physical world. Experts have estimated that 3D printers might produce only 5% of all consumer goods in the coming years, yet it is possible that it could be more like 90% (Johnston et al., 2018). Millions of jobs could hang in the balance. A recent analysis by the World Economic Forum (Rodrik, 2018), has estimated that 3D printing, robotics, and other advanced technologies could contribute to a loss of five million jobs from major economies in the next five years. But other studies (Garrett, 2014; Gebler et al., 2014) have concluded that 3D printing could be part of a new Industrial Revolution 4.0 or society 5.0, eliminating the advantage of cheap labor in such places as China, bringing production back to the USA, and completely reimagining the concept of international trade as most things could be manufactured locally.

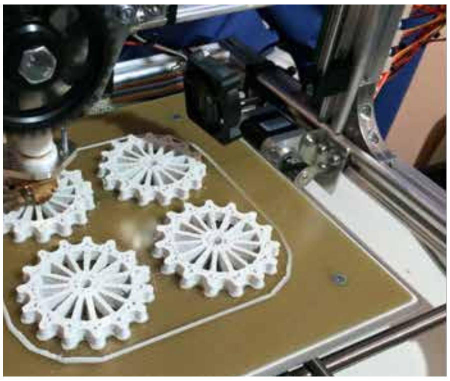
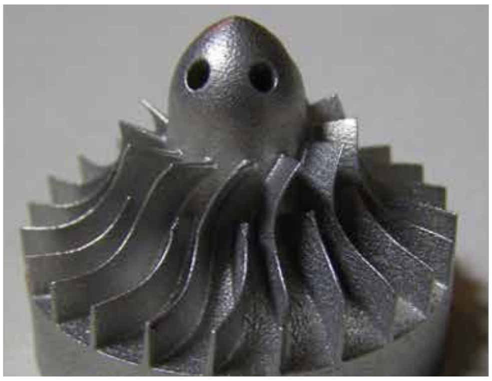


Figure 21. 3D-printed products. From left to right: robot printing continuous tracks. Source CuriosityII - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=37221284; 3D-printed miniature turbine from Rapid 2006 in Chicago, Illinois. Source: Bcn0209 at English Wikipedia, - “snapshot of an image I took.” Transferred from Wikipedia to Commons by Calliopejen1 using CommonsHelper, Public Domain, https://commons.wikimedia.org/w/index.php?curid=16958731; side view of Defense Distributed “Liberator” 3D-printed hand gun. Source: NotLessOrEqual – Own work, CC0 1.0, https://commons.wikimedia.org/w/index.php?curid=59334489.

5.3.2 Financial Services

The implications of digitalization in the financial sector seem to be enormous. In 1914, economist William Scott defined the four main services that commercial banks had to offer as (i) safekeeping of money and other valuables, (ii) payments, (iii) loans, and (iv) investments (Scott, 1914). Apart from the addition of insurance, these services have remained mostly unchanged (McWaters, 2015; UNSGSA, Better Than Cash Alliance, UNCDF, & World Bank, 2018), but the methods and customer expectations of delivering them have profoundly changed and are continuing to undergo change. The locality and physical reality of financial services have been transformed: in developed countries, digital distribution of data and networked systems driven by convenience and cost reduction are prevalent (de Almeida, Fazendeiro, & Inácio, 2018), and in developing countries there has been increasing access to and inclusion in financial services (UNSGSA et al., 2018).

The World Energy Forum and Deloitte identified 11 disrupting clusters of innovations related to digitalization. These innovations will exert pressure on the traditional financial services model in the near future (McWaters, 2015) (Figure 22).

In line with other industry studies, consumers will continue to need financial services, but they will embrace less localized and decentralized solutions (PWC, 2016). The sharing economy is foreseen to become embedded in financial products, including peer-to-peer lending, and cashless and payment-integrated services (such as Uber and Amazon).

Traditionally, banking systems were largely impenetrable for new entrants. With the digital transformation, small and agile new suppliers have

Figure 22. Disruptive innovation clusters in the six key financial services. Source: McWaters (2015).

appeared in large numbers, and incumbents are losing leverage unless they adapt to the new financial ecosystem (McWaters, 2016). Financial technology (FinTech) disruptors are usually fast-moving, responsive start-up companies that generally focus on a particular innovative technology or process. They have been invading various services, from mobile payments to insurance, and have more than tripled annual global investments in the last five years (PWC, 2016). The banking industry has recently seen the introduction of numerous online only or direct banks (e.g., N26[10]), many of which offer worldwide access.

Data and analysis are becoming key to revenues and profitability. Customer intelligence based on big data, but then translated to tailored services, is predicted to shape the future of service requirements. Financial services and technology companies use artificial intelligence to explore social and emotional intelligence, natural language processing, logical reasoning, pattern assessment, sensors, mobility, navigation, and more. The services created are expected to substitute the traditional bank cashier to supply a more personalized treatment.

10 https://www.n26.com/en-us/

The current transformations of infrastructure will become the norm. Many banks already use cloud-based software-as-a-service (SaaS) applications for non-core processes, but shortly these will be the main (or only) platforms for all business activities. On the customer side, mobile and online services will become the norm. Globally, mobile accounts have reached half a billion people, 277 million of whom live in sub-Saharan Africa (Lashitew et al., 2019). In light of this, cyber security becomes a critical threat to be overcome.

The digital financial transformation can contribute to the development of a financial inclusion regime. Mobile money in Kenya has become a key part of the economy (Box 8), and 70% of the adult population in Kenya use mobile money services (Lashitew et al., 2019). The online banking services far outnumber the traditional banking access in many developing countries.

Financial inclusion means that formal financial services (e.g., savings, payment services, loans, and insurance) become easily accessible for all consumers (GFPI, 2011). However, the current level of access is still limited, even if it is growing. Financial exclusion largely affects the poor, but even the middle classes in developing countries, amounting to 45% of adults

Box 8. Kenya: A Digital Revolution Success Story

Kenya has become one of the digital leaders in Africa in a relatively short period of time. Its success is due to many years of consistent support by the Kenyan government and a determined strategy that has included programs to help its population become digital-ready as well as investments in infrastructure. The percentage of the population with access to the Internet is higher in Kenya than in other African countries. It also has the highest use of mobile phones for financial and other transactions (Banga & te Velde, 2018). This is even more extraordinary given that in 1982 the Kenyan government banned the use of computers in public offices to prevent the new technologies from eliminating the need for secretarial jobs. Today, Kenya includes programs to address the Digital Revolution as one of its development pillars in its 2030 Vision (Ndemo & Weiss, 2016).

Kenya is an example of a developing economy where the Digital Revolution has thrived. In the services sector, digitalization has helped to create new jobs, particularly in the provision of financial services. M-Pesa, the mobile based transfer facility established in Kenya in 2007, has revolutionized the financial services industry not only in Africa but also in many developing countries across the world. Digitalization has also helped to increase labor productivity in the agriculture and manufacturing sectors, especially in the production of machinery, in electronics, and in the transport sector; rapid advances are also being made in the chemicals, plastics, and rubber industries (Banga & te Velde, 2018).

The success of Kenya is due to a combination of factors that helped the Digital Revolution take hold. One of the most important was a five-point policy that consisted of (i) programs dedicated to the development of the information and communication technologies (ICT) infrastructure; (ii) creation of relevant content that supported the development of Kenya; (iii) a focus on creating the appropriate skills and building human resource capacity; (iv) promotion of entrepreneurship, start-ups, and public–private partnerships; and (v) a program dedicated to the creation of jobs for Kenyan youth. This last point was particularly important given Kenya's high rate of youth unemployment. Another key factor was the impact that the first fiber optic cable, which was introduced in the Eastern Seaboard of Africa, had on lowering the cost of communications. This helped to mainstream Internet access in universities and start-up hubs that were created at subsidized rates. The success of M-Pesa, particularly its increase in subscribers, was helped by this development. Finally, the important development of the Kenya Open Data Initiative supported the creation of new apps and new entrepreneurs (Ndemo & Weiss, 2016).

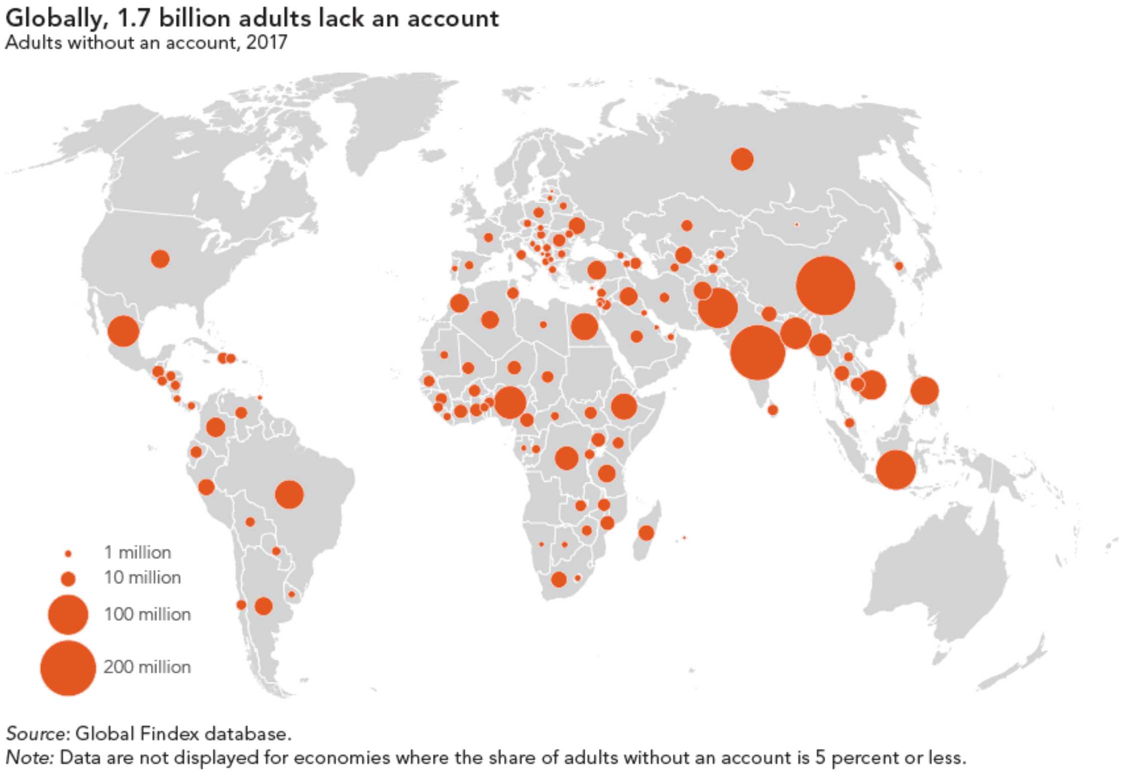

Figure 23. Financially excluded population worldwide. Source: Asli et al. (2018), CC BY 3.0.

(or nearly two billion people), do not have a financial account at all (Manyika et al., 2016) (Figure 23).

Financial inclusion helps create the conditions that ultimately bring many of the SDGs within reach (UNSGSA et al., 2018).

When people are included in the financial system, they have increased chances to move out of poverty, for example through access to business or education investment opportunities (Klapper et al., 2016). Digital financial services help families save money and cope with risks and shocks. Businesses can have access to innovative rating systems and expand access to low-cost loans. Payments via digital services increase fairness through their transparency (e.g., reduction in bribes; Muralidharan et al., 2016) and by making sure the salary reaches those who have actually worked for it. For example, in Burkina Faso, savings are three times more common among those with mobile money than those without (Ky et al., 2017).

Financial inclusion can help increase access to faster, safer, more efficient, and cheaper payments for farmers, thus contributing to a reduction in hunger (UNSGSA et al., 2018). Access to credit to invest in improved production (agricultural or industrial), as well as access to insurance, can better secure earnings (UN Global Compact & KPMG, 2016).

While rural areas can be better connected by using digital services, cities face different challenges (SDG 11). Cities are congested and people in cities waste time in administrative tasks. Electronic solutions can reduce participation time, and cash collection dependency can increase flexibility of collecting and paying fees and dues (UNSGSA et al., 2018). In particular, public services, such as transportation, can benefit from time and cost savings. In Colombia, for example, smart public transport transit cards increased the use of public transport by 56% in one year. In Sweden, digital congestion charges in Stockholm reduced traffic volume by 22% in a few weeks and congestion by 30–50%. In addition, government transfers through digital services reduce operational costs. For example, in India, a switch from cash to smart cards reduced requested bribes by officials by 47%. Governments can capture about 20% of leakages when using digital payments, alternative data sources, and advanced analytics. This amounts to a trillion dollars of savings (UNSGSA et al., 2018).

One of the most disruptive digital technologies to impact the financial sector in recent times has been cryptocurrencies. Digital currencies and other innovations in payment systems could increase the speed of domestic and cross-border transactions, reduce transaction costs, and eventually broaden access to the financial system for poor and rural households. In a recent article, CBInsights (2018) identified six key areas where blockchain could disrupt the financial services sector:

1. Payments: by establishing a decentralized ledger for payments (e.g., Bitcoin), blockchain technology could facilitate faster payments at lower fees than banks;
2. Clearance and settlement systems: distributed ledgers can reduce operational costs and bring us closer to real-time transactions between financial institutions;
3. Fundraising: Initial Coin Offerings are experimenting with a new model of financing that unbundles access to capital from traditional capital-raising services and firms;
4. Securities: by tokenizing traditional securities, such as stocks, bonds, and alternative assets – and placing them on public blockchains – blockchain technology could create more efficient, interoperable capital markets;
5. Loans and credit: by removing the need for gatekeepers in the loan and credit industry, blockchain technology can provide lower interest rates and make it more secure to borrow money;
6. Trade finance: by replacing the cumbersome, paper-heavy bills of lading in the trade finance industry, blockchain technology can create more transparency, security, and trust among trade parties.

Digitalization has already had a significant impact on global stock markets. In 2010, high-frequency and algorithm trade accounted for 60–70% of trading in the USA. By 2017, J.P. Morgan reported that traditional traders represented a mere 10% of trading volume. More recently, machine learning and artificial intelligence have entered the sector. In 2017, Wall Street had its first fully artificial-intelligence-powered Equity Trading Fund (ETF). In the first week of operations, it outperformed the S&P 500 index. Remarkably, by August 2018 its shares rose by 20%. ETF operates on the premise of IBM Watson, a supercomputer that processes and analyzes news and reports relating to 6,000 American companies. Additionally, Watson's continual learning capabilities allows it to examine its own performance; hence, the algorithm can learn from its mistakes (e.g., unprofitable transactions) to make better decisions in the future (Zamagna, 2018). One of the fastest growing technologies is "robo-advice", which uses artificial intelligence and machine learning to "replace" traditional financial advisers in the provision of investment advice to consumers. According to the World Bank, the value of assets under robo-advice management was greater than US$400 billion in 2018 and is expected to grow to almost US$1.5 trillion by 2023.

5.3.3 The Future of Work

Throughout human history, there have been fundamental shifts in the nature of work. At first, the primary sector (agriculture) occupied most people; then, during the Industrial Revolution, the secondary sector (manufacturing) attracted more and more workers, offering higher productivity and less exposure to weather-related agricultural yield fluctuations. Over the last century, we have seen a transition from manufacturing to the tertiary sector (services). This transition, often referred to as deindustrialization, has resulted from growing automation of manufacturing activities, increased wealth, and new needs for immaterial goods to improve human welfare. Deindustrialization has been apparent even in low-income developing countries (with the exception of Asia), where it has been driven not by rising incomes or technological changes within a country's borders, but by, among other things, technological changes taking place elsewhere and affecting these countries through globalization and trade (Rodrik, 2016).

In the future, technological change and digital transformation will certainly improve productivity in these sectors. However, there will also be structural implications for occupations and working hours. Exponentially increasing computing power and machine learning will give rise to autonomous machines with cognitive and decision-making abilities, which will have a disruptive impact on the workplace. On one the hand, these developments will help to automatize a significant portion of daily working routines, providing workers with more free time, increasing the wellbeing of the labor force, and creating more consumption of recreational services. On the other hand, many low-skill jobs in the primary, secondary, and tertiary sectors may become redundant in a future where artificial intelligence will effectively replace humans in performing cognitive tasks and some decision-making routines in the workplace. Some predict the disappearance of hundreds of millions of jobs. Robotics and artificial intelligence alone could take away some 800 million jobs by 2030, with many of these in emerging and developing countries (Manyika et al., 2017). The number of industrial robots is increasing rapidly across the world (Figure 24).

Work plays an important role in providing individual income, identity, societal status, and meaning. It is, therefore, critically important to address the risk of an increasing number of workers being replaced by machines, especially if opportunities to pursue other meaningful and income-generating occupations are not offered. There is a danger that many workers will be displaced, and that only highly educated, well-to-do professionals, and those in "last-mile" jobs, will be secure in their occupations (Free exchange, 2019). Some argue that the focus should not be so much on the loss of jobs (most jobs cannot be fully automated) but on the transformation of jobs to the point of not being recognizable (Fleming, 2019). Consequently, it will be important to reinvent and reengineer jobs to benefit society. Learning the dynamics of these

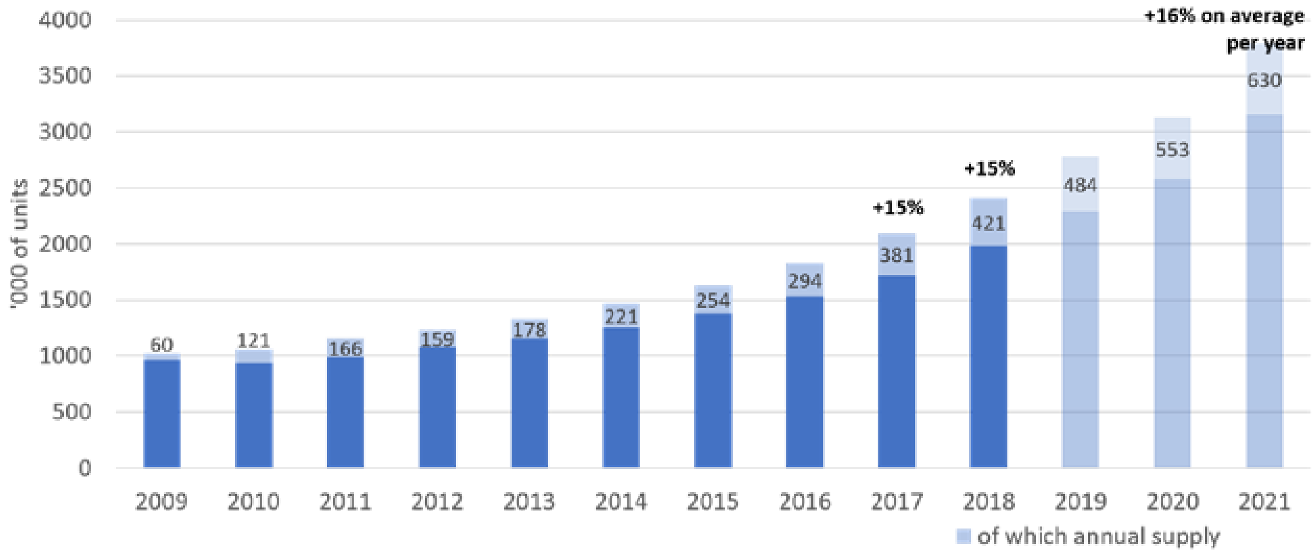

Figure 24. Estimated worldwide operational stock and supply of industrial robots since 2009, with a forecast for 2018–2021. Source: Data from IFR (2019).

transformations is key to enabling policy and decision makers to design coping and adaptation strategies that minimize the negative impact of the workplace transformation. Norway is a good example where the risk of automation is said to be among the lowest in the OECD (Arntz et al., 2016). One reason for this is that Norway is more advanced than most in automation, so many jobs have already been transformed to contain a greater social component (Nedelkoska & Quintini, 2018).

Historically, many economic sectors have become obsolete, creating temporary unemployment that is then absorbed by the rise of new sectors (Frankel, 1955). The Digital Revolution will accelerate a decline in low-skill jobs across sectors that is unlikely to be quickly absorbed by the market. This calls for governance and forward-looking policies to buffer the impact of the digital transformation on the workplace and steer it in the direction of achieving SDG 8 (decent work for all). An obvious response is to boost workers' skills through education, but this faces challenges as it (i) takes time to retrain humans to fit the changed reality of the workplace, (ii) requires substantial public investment at a time when public finances are severely constrained by large debt burdens, and (iii) is subject to uncertainty about what skills will still be in demand in a world where many cognitive and decision tasks are being performed by machines.

The decline of low-skill jobs and their replacement by automation across many sectors has some additional consequences for many developing countries. The traditional development model which these countries have used as an engine for growth is based on the following: cheap labor means that manufacturing and domestic output is competitive and can easily be traded across borders, so it is not inhibited by demand and incomes at home; the know-how for manufacturing is also relatively easy to transfer across borders (including from rich to poor countries); and manufacturing, in most cases, does not make immense demands on skills (Rodrik, 2018). The new technologies change this traditional model significantly in several ways, including in terms of skills required and the ease (or not) of know-how transfer. Developing countries face greater challenges when it comes to designing and implementing strategies to cope with these changes.

The literature suggests that the jobs most vulnerable to being taken over by machines are low-skill jobs centered on routine tasks (Acemoglu & Autor, 2011). Such jobs are prominent in the mobility sector (threatened by autonomous vehicles), on the office floor (threatened by automatized decision making, such as for administrative and accounting tasks), and in households (threatened by further automatization of household tasks). Up to half of all jobs are at risk of automatization in some mature economies (Frey et al., 2016), and around two thirds in developing economies (World Bank, 2016). But the impact could be even more far reaching, with machines taking over some high-skill jobs centered on analytic and diagnostic tasks. This could, for example, include occupations such as brokers, pharmacists, programmers, and data analysts.

At the other end of the spectrum, jobs that require perception and manipulation, creativity, inspiration, and emotional bonding seem to be most secure (Frey et al., 2016). Examples are teachers, nurses, social workers, scientists, actors, entertainers, politicians, civil society agents, managers, and leaders. Currently, those jobs constitute only a small fraction of the workforce. Therefore, it will likely be necessary to broaden our concept of contractual work to include activities like child raising, care giving, community services, and voluntary social work. Such occupations are deeply human in nature and so are unlikely to be taken over by machines; even if these occupations are assisted by machines (e.g., in care-giving occupations), humans will likely continue to play the central role. These activities have always provided critical meaning to individuals and are of high value to society, but they are mostly not rewarded as contractual work and are still discounted with regard to societal status (in contrast to their societal value).

The creation of a new service sector, remunerating voluntary, care-giving, and social work according to their societal value could absorb redundant workers from other shrinking sectors. It might also offer these newly absorbed workers an even greater sense of identity, meaning, and belonging, in line with SDG 8. However, it would require a substantial redistribution of economic income from other sectors to these activities, and it is likely that this would have to be organized by governments or other public institutions. Therefore, it would require changing the capitalist economic model, which relies on private ownership of production and private consumption. This could be aided by the overall increase in wealth generation due to expected large productivity gains from deploying autonomous machines. The key will be to channel some of this additional wealth to public rather than private ownership, and to use it to fund the new service sector as well as education and life-long learning. Policy proposals like a robot tax have already been developed that aim to achieve this goal.

In one way or another, most countries are becoming increasingly aware of the challenges and potential benefits of the Digital Revolution. Many are designing strategies to mitigate the negative effects while also reaping the benefits of these new technologies. But many developing countries need support in order not to be excluded or marginalized from this great transformation. Failure to address the potential downsides will have major impacts on inequality and social stability. With more research and more literature focusing on what developing countries need to do to face the huge challenges of tapping into this new revolution, some of the dire predictions will hopefully give way to more optimistic prognoses. An increasingly large body of literature focusing on the positive agenda of developing countries is starting to appear. A report by the World Bank (2016) presents a cautiously optimistic outlook on the digital transformation and the potential benefits for developing countries, but it also highlights the stark reality. According to this report, the broader development benefits from the Digital Revolution are far from being realized. This is an understatement. Some six billion people do not have the high-speed Internet access required to benefit from the digital transformation (see 4.2). For most of the world's population, Internet access is unaffordable and inaccessible. Moreover, the necessary investment in infrastructure is currently beyond the means of many developing countries. And the governance that is required to tap into this digital world with appropriate policies and regulations is often weak.

5.4 Decarbonization & Energy

5.4.1 Energy Systems

Energy systems have been decarbonizing since the beginning of the Industrial Revolution. The replacement of traditional energy sources by coal eventually improved the overall efficiency of the system and reduced carbon intensity (coal has less carbon than biomass per unit energy). Further evolution toward oil and gas reduced yet again the carbon intensity of energy, and the current rapid penetration of renewables, together with nuclear and large hydropower, contribute toward decarbonization. For example, natural gas has half the emissions of coal. Thus, the trend is clear, although it is not fast enough to

Box 9. Narrative for 2050: Decarbonization & Energy, Energy Access, Efficiency, Electrification, Decent Services

The world has largely decarbonized, and this has been accompanied by universal access to clean, affordable modern energy services. The seeds of this transition can be seen in rapid technology development and new behaviors in key sectors, such as renewable energy, electric mobility, and zero-energy buildings. By 2030, greenhouse gas emissions have fallen by half compared to 2020, as all nations start to follow deep decarbonization pathways toward net-zero emissions. Focus is on the provision of clean and environmentally sustainable energy services, whereby energy supply is a combination of both centralized and decentralized systems, with high energy efficiency standards being the norm everywhere. Together with behavioral change and technological innovation, this leads to reduced energy demand and large savings on the energy supply side. Moreover, there are reinforcing feedback loops enabled by government incentives and other dynamics; for example, there is huge investment in sustainable, resilient, and efficient infrastructure, and there are technological breakthroughs and cost decreases, sector coupling and digitalization, and lifestyle changes and energy self-sufficiency.

offset increases in demand. As a result, there have been ever-growing greenhouse gas emissions.

Carbon dioxide (CO_2) emissions increased last year by more than 2%, which is in line with the historical average rate during the past century and a half. Decarbonization is comparatively slow at about 0.3% per year. To meet the Paris Agreement and SDG 7 targets, both efficiency and decarbonization have to increase rapidly. By mid-century, the global energy system should be completely decarbonized, but this will require the share of renewables to double by 2030 while emissions halve. This all requires herculean efforts. Increasing the share of renewables, as well as nuclear energy in countries where it is acceptable, are further steps in the right direction as they reduce the carbon intensity of energy.

Furthermore, a shift toward renewables is also a shift toward smaller units, with large possibilities for technological learning and price reductions along the experience curves. For example, the cost of photovoltaics has declined by two orders of magnitude, and wind is today often the cleanest source of energy. Smaller units and decentralization need a higher degree of interconnectedness of the system through electric (and gas) grids, together with rapid deployment of smart systems and digitalization. Electric mobility and ever more efficient houses and industrial processes are furthering this trend toward digitalization.

Consequently, the energy sector has been an early adopter of information technology systems, notably in oil and gas, electricity, and heavy industry. Today, digital technologies can be found in all energy demand and supply, helping to improve the safety, productivity, accessibility, and sustainability of energy systems worldwide. Rapid advances in data, analytics, and connectivity are accelerating the digitalization of energy, opening the door to new models of producing and consuming energy, while also raising new security and privacy risks (IEA, 2017).

Transport is becoming increasingly electrified, smarter, and more connected, improving safety and efficiency. Digitalization could have its biggest impact on transport (see section 5.5.1), where connectivity and automation (alongside further electrification and shared vehicle use) could dramatically reshape mobility by complementing public transport systems. The overall net impacts on energy use are highly uncertain, because they hinge on the interplay between technology, policy, and behavior.

In buildings, digitalization could cut energy use by about 10% by using real-time data to improve operational efficiency (IEA, 2017). For example, smart thermostats can anticipate the behavior of occupants (based on past experience) and use real-time weather forecasts to better predict heating and cooling needs. Digital energy services could also allow consumers to become more active participants in the energy system (see section 5.5.2 on smart meters and devices). Smart and positive-energy buildings would essentially not require any net energy from the grid (see section 5.5.2).

In industry, many companies have a long history of using digital technologies to improve safety and increase production. Further cost-effective energy savings can be achieved through advanced process controls, and by coupling smart sensors and data analytics to predict equipment failure. Machine learning, 3D printing, and connectivity could have even greater impacts (see section 5.3).

The oil and gas industries have long used digital technologies, notably in upstream processes, and significant potential remains for digitalization to further enhance operations. Widespread use of digital technologies could decrease production costs between 10% and 20%, including through advanced processing of seismic data, the use of sensors, enhanced reservoir modeling, and improved three-dimensional steering for drilling (IEA, 2017; Odintsova et al., 2018).

In the coal industry, digital technologies are increasingly being used in geological modeling, process optimization, automation, predictive maintenance, and improvements to worker health and safety. However, the overall impact of digitalization may be more modest than in other sectors because deep decarbonization would marginalize coal use without carbon capture and storage (GEA, 2012).

In the power sector, digitalization has the potential to save around US$80 billion per year, or about 5% of total annual power generation costs (IEA, 2017). Digital technologies can help to reduce operating and maintenance costs, improve power plant and network efficiency, reduce unplanned outages and downtime, and extend the operational lifetime of assets.

Digitalization could fundamentally transform the energy system by breaking down boundaries between energy sectors, increasing flexibility, and enabling integration across systems. The electricity sector is at the heart of this transformation, because digitalization is blurring the distinction between generation and consumption (Figure 25). Digitalization enables four interrelated opportunities: (i) smart demand response and increased system flexibility; (ii) greater integration of variable renewables; (iii) smart charging of electric vehicles to provide further grid flexibility; and (iv) better coordination of distributed energy resources (e.g., rooftop solar photovoltaic panels and storage) (IEA, 2017). Further examples are given in Box 10.

However, the information and communications technologies that make all these benefits possible also require ever more energy. As billions of new devices become connected over the coming years, they will

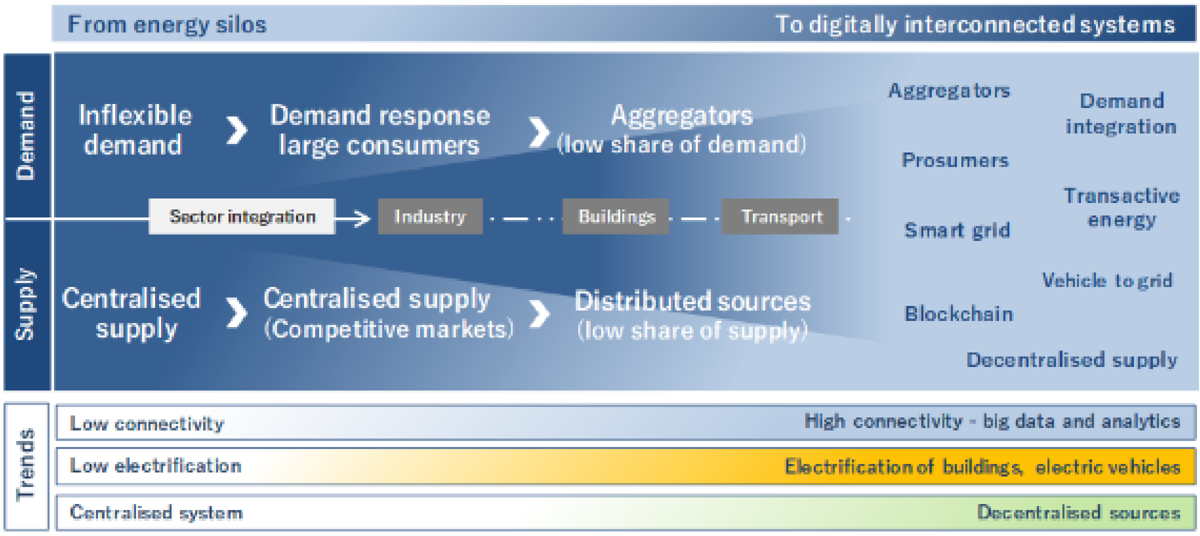

Figure 25. Possible steps in the digital transformation of the electricity system. The deployment of digital technologies is creating a more interconnected and responsive electricity system, with the potential to help increase flexibility, efficiency, and reliability. Source: IEA (2017).

Box 10. Digitalization, decentralization and open data can transform the power sector

By leveraging digitalization and data analytics to integrate decentralized renewable energy technologies, utilities have new alternatives to grid extension, faulty transformers, and unprofitable connections. By encouraging collaboration with decentralized renewable energy companies, utilities can find more cost-effective ways of leveraging smart meters, storage, and distributed generation to enable reliable, affordable, and universal energy access.

Based on policy targets and regulations, traditional energy planning often relies on expensive consulting firms to conduct baseline studies of energy use, load forecasting, and generation requirements for future use. This old style of energy planning for 10 – 20-year timelines forecasts future demand as well as how demand will be met by central grids for the already connected. Moreover, this consultant-based approach is often led by technical institutions and consultancies using a variety of software tools and proprietary data sets, tools, and data that the governments who commission the work may not own or have the capacity to use.

Digitalization enables integrated planning that is dynamic, open, data-driven, and optimized to deliver least-cost, fastest-path universal energy access. Affordable low- or no-cost modern tools (including the World Bank's Electrification Pathways, the University of California at Berkeley's Grid Access Planning model, or the Massachusetts Institute of Technology's Reference Electrification Model) use publicly available data to evaluate the least-cost means for a regional or national power system to meet demand by concurrently modeling generation, transmission, distribution, investments, and operational costs. Not only are these approaches faster and more cost effective to execute, grid access planning analysis suggests that an electrification strategy that fully integrates decentralized renewable energy technologies creates savings of 15% to 20%, compared to traditional grid extension models, to supply the same number of customers.

Just as traditional planning tools must be adapted to meet the needs of low-energy-access countries, traditional electrical grids and business models must evolve to deliver sustainable, universal and affordable energy to all. Currently, most sub-Saharan African countries suffer grid inefficiencies that affect billions of people every day, including transmission and distribution losses as high as 50% and service interruptions of more than 500 hours per year. Altogether, hundreds of millions who are currently connected to power grids fail to have reliable energy access.

Thanks to digitalization and decentralization, traditional utilities do not need to solve these problems alone. Today, comparatively inexpensive next-generation-related digitized technologies, such as integrated smart meters, predictive tools like Gridwatch (which uses cell phone charging outages to predict transmission failure), and remote monitoring systems can help create an intelligent network that taps mini-grids or networked rooftop systems to deal with distribution issues, transmission outages, and demand response. Switch, sectionalizer, and recloser automatization in medium voltage networks can drastically reduce the duration and extension of outages by isolating the fault and restoring the system. Integrated DRE technologies can improve the reliability of connections, reduce grid losses, and improve power quality and overall utility performance, while simultaneously creating sustainable businesses on both sides of the wires.

To achieve this, a process that guarantees system-level coordination between energy sources, such as a distributed system operator, can orchestrate the interaction between the physical grid, the distributed resources, customers, third-party providers, and the transactions between them. Technology platforms that enable data harmonization in the digital environment are needed. The management of this amount, and type, of information will require high privacy and security standards; most likely, it will involve anonymizing and sharing customer data between solar-home systems, mini-grid and grid systems, while also maintaining alignment with General Data Protection Regulations.

Digitalization, decentralization, and open data do not mean that national grids will be going out of business any time soon; rather, there are numerous new business opportunities that include use fees for sub-concessions, shared incentives for new connections, and reduction of capital expenditures by relying on decentralized renewable energy technologies for network support. There is a new future for national grids in countries with low energy access: these grids can act as "base stations" in a network of networks that can interconnect many points of generation, storage, and consumption necessary for providing universal energy access. By engaging directly with the companies that provide the digital, decentralized, and data-driven technology, utilities can help identify the critical path technology, processes, and regulatory interventions needed to transform their national energy systems into robust networks that deliver reliable, affordable, and universal access for all.

require electricity and will drive growth in demand for – – and energy use by – – data centers and data transmission network services. Data centers and networks together account for around 2% of global electricity use. Sustained gains in energy efficiency could keep demand growth largely in check over the next few years (IEA, 2018a), and they may even decrease energy use through efficiency gains of new devices (Grubler et al., 2018). Over the longer term, information and communication energy use is uncertain. Clear policies and standards need to offset the historical tendency of demand growth resulting from efficiency improvements. Clearly, demand growth arising from the efficiency of new devices and equipment is desirable for decent access to energy services in the developing parts of the world (GEA, 2012).

Although digitalization can bring many positive benefits, it can also make energy systems more vulnerable to cyberattacks. Cyberattacks are becoming easier and cheaper to organize, and the growth of the Internet of Things is increasing the "cyber-attack surface" in energy systems. Privacy and data ownership are also major concerns for consumers, especially as more detailed data are collected from a growing number of connected devices and appliances. At the same time, aggregated and anonymized individual energy use data can improve understanding of energy systems, such as load profiles, and help lower costs for individual consumers.

All energy sector stakeholders have a role to play in enhancing the digital resilience and security of an increasingly connected energy system. With solutions and processes producing and using vast volumes of data, questions remain around how best to balance the risks and opportunities of data-driven solutions. Digitalizing traditional energy infrastructure will require careful management, given the inherent limits to interoperability.

Policy and market design are vital to steering digitally enhanced energy systems onto efficient, secure, accessible, and sustainable development pathways. For example, digitalization can assist in providing electricity to the roughly one billion people who still lack access to it (IEA, 2018b). New digital tools can promote sustainability; for example, satellites can verify greenhouse gas emissions, and devices can track air pollution at the neighborhood level.

While there is no simple roadmap to show how an increasingly digitalized energy world will look in the future, the IEA (2017) outlines 10 "no-regrets" policy actions that governments can take to prepare:

1. Build digital expertise within their staff
2. Ensure appropriate access to timely, robust, and verifiable data
3. Build flexibility into policies to accommodate new technologies and developments
4. Experiment, including through "learning-by-doing" pilot projects
5. Participate in broader inter-agency discussions on digitalization
6. Focus on the broader, overall system benefits
7. Monitor the energy impacts of digitalization on overall energy demand
8. Incorporate digital resilience by design into research, development, and product manufacturing

9. Provide a level playing field to allow a variety of companies to compete and serve consumers better
10. Learn from others, including both positive case studies and more cautionary tales.

5.4.2 Climate

Clearly, the impact of the Digital Revolution on the energy, transport, and production and consumption sectors could have significant positive consequences for climate change mitigation. Reduced greenhouse gas emissions from a more efficient and increasingly renewables-based energy sector, rising uptake of electric vehicles, and a more efficient and less wasteful manufacturing sector will go a long way to ensuring an increasingly decarbonized world, as called for by the SDGs and the Paris Agreement. Similarly, a more technology-driven, intensified, high-yielding, and efficient agriculture and land use sector, with improved water management, will help reduce emissions. Smart buildings, infrastructure, and cities will significantly decrease energy demand and associated climate impacts.

One of the most significant advances technology has brought to climate science and climate change mitigation is the development of advanced sensor technologies. Access to accurate, real-time, and precise location environmental data is critical for both climate monitoring and mitigation efforts. Smart sensors are becoming ubiquitous in almost every sector relevant for climate change: they can measure CO2 and methane emissions from the energy and agricultural sectors, and pollution from the manufacturing and transport sectors. In a recent landmark study, researchers, using a range of advanced sensor technologies mounted on drones, aircraft, and cars, measured methane emissions from the USA oil and gas industry supply chain, finding that emissions were ~60% higher than the Environmental Protection Agency (EPA) estimates (Alvarez et al., 2018). The authors stated: "These data, and the methodology used to obtain them, could improve and verify international inventories of greenhouse gases and provide a better understanding of mitigation efforts outlined by the Paris Agreement." They added: "Substantial emissions reductions are feasible through rapid detection of the root causes of high emissions and deployment of less failure-prone systems." Advanced satellite technologies are also playing a role in climate monitoring. The initial Landsat program (with Landsat 9 due for deployment in 2020) monitors a range of climate-related activities, such as glacier and ice sheet melt, wildfires, deforestation, urbanization, and so on. Methane-SAT, due for launch in 2021, is designed to continuously map and precisely measure methane emissions almost anywhere on the planet, making it possible to "see" emissions in places that are difficult to track today.

The widespread deployment of sensor technologies is increasing the volume of data available for analysis. In a recent review paper on big data and climate change, Hassani, et al. (2019) produced a framework for how big data can be, and is being, used in climate change studies (Figure 26). They see the primary roles for big data as observation and monitoring, understanding, predicting, and optimizing. Analyzing such large data sets is computationally complex and demanding. As the volume of data increases exponentially, the need for concomitant advances in data storage and computational architecture and power cannot be underestimated (Fan et al., 2014).

Blockchain is an emerging digital technology platform that offers a promising contribution to climate action. In a recent report, Navigating Blockchain and Climate Action, the Climate Ledger Initiative (CLI, 2019) identified three areas where blockchain technologies could play a role: (i) next-generation registries and tracking systems, as the decentralized nature of the Paris Agreement and its governance structure requires new approaches to registries and tracking systems to handle heterogeneous rulesets for accounting and reporting and to enable trusted, networked carbon markets; (ii) digitizing measurement, reporting, and verification, facilitating access to carbon markets or other results-based finance schemes, and transforming corporate supply chains toward more transparency and accuracy on climate and sustainability impacts of goods produced and sourced; and (iii) decentralized access to clean energy and finance, with blockchain systems emerging as the backbone of new decentralized markets for clean energy empowering individual "prosumers" to produce and store their own renewable energy and trade with their neighbors.

The Digital Revolution has enormous capacity to educate and influence the public on issues related to climate change. The power of the Internet, and particularly social media, to mobilize citizens is already clearly evident. This power is increasingly being used by governments, businesses, and special interest groups to "nudge" citizens and consumers to change their behaviors. While this has considerable upsides by encouraging people to be more sustainable and "climate aware", especially when it comes to understanding the impact of their behavior and consumption patterns on the environment, there are associated problems due to the spread of misinformation or increased consumerism.

Although the Digital Revolution undoubtedly has the potential to provide huge climate benefits as outlined above, there is also a potential downside. With more than 25 billion connected devices in 2019 (Abdelmohsen et al., 2015), growing to an estimated 75 billion by 2025 (Figure 27), the increasing energy demands of digitalization cannot be overlooked.

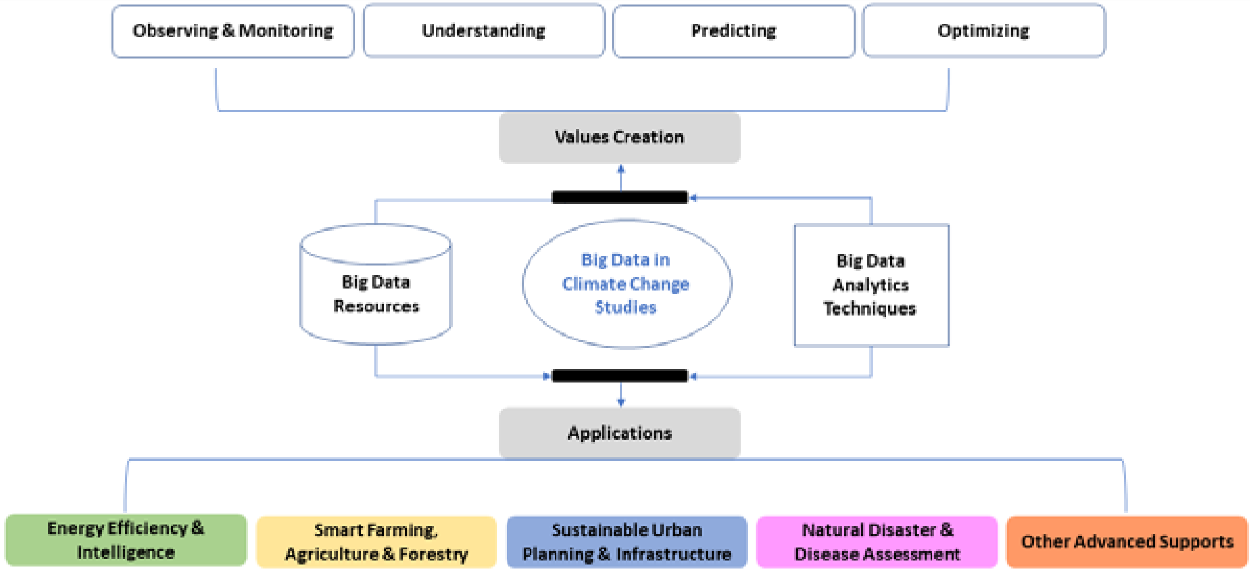

Figure 26. Framework of big data in climate change studies. Source: Adapted from Hassani et al. (2019).

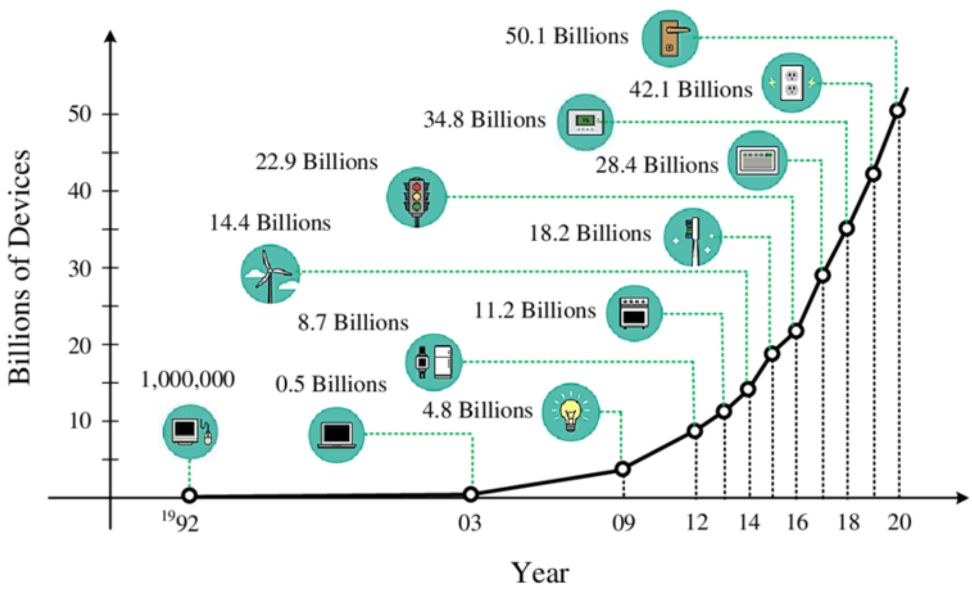

Figure 27. Expected number of connected devices to the Internet. The data are obtained from recent reports developed by Cisco and Ericsson. The reports discuss the expected growth in the number of connected devices by 2020 due to the introduction of the machine-to-machine market. Source: Abdelmohsen et al. (2015), https://arxiv.org/abs/1506.06216.

Overall, the digital economy is estimated to account for about 7% of the world's electricity consumption, and this is forecast to rise to 12% by 2020, with a projected annual growth rate of 7% (Morley et al., 2018). The energy consumption of the Bitcoin network already exceeds that of some countries (de Vries, 2018). Although some have argued that increasing digitalization may be unsustainable from an energy, and hence climate, perspective (Røpke, 2012), others have emphasized that energy efficiencies and low energy demand resulting from digitalization can help achieve the Paris climate targets (Grubler et al., 2018).

Stabilizing the climate in accordance with the Paris Agreement presents a major challenge, because it means that all emissions need to decline to net-zero by mid-century. But even this would not be enough, as the world has already gone beyond 1°C increase in global mean temperature compared to the pre-industrial period. So, there is only 0.5°C to go to the Paris temperature limit, meaning that some net-negative emissions will be needed beyond 2050 when net-zero would be achieved. Afforestation and carbon capture and storage in conjunction with sustainable biomass are possibilities to achieve negative emissions (namely, resulting in net removal of carbon from the atmosphere). Digitalization can play a key role in this

Box 11. Narrative for 2050: Food, Biosphere & Water, Sustainable Intensification, Biodiversity, Forests, Oceans, Healthy Diets, Nutrients

The 2050 vision requires the sustainable use of land that provides sufficient and healthy food for all and supports global biodiversity. By 2030, global agricultural productivity is increased through sustainable intensification of the agricultural sector with the adoption of agro-ecologic elements and better functioning of agriculture markets. At the same time, food waste and loss are significantly reduced. The agricultural demands for freshwater are also reduced, and the expansion of agricultural land has halted to preserve remaining biodiversity and enhance the resilience of carbon sinks. Improved management of artificial fertilizers greatly reduces nutrient pollution of marine and freshwater ecosystems. Hunger and malnutrition are eliminated, and there is year-round universal access to clean, safe, and nutritious food. Worldwide, diets are significantly healthier, implying reduced reliance on meat. This means that food production has changed its resource base to some extent by 2030 and more distinctly by 2050. With new innovative approaches, the agro-structure changes so that it is no longer as resource intensive as it is today. Food waste and food loss can be significantly reduced through more localized distribution. Fish stocks and other marine resources are sustainably managed, and levels of marine pollution significantly reduced, with improvements to the health of marine ecosystems. Taken together, these changes have allowed biodiversity loss to be dramatically reduced and often brought to a definite halt. Food systems and other anthropogenic land and marine use serves to store carbon and enhance biodiversity.

direction, as discussed in the next section on food, biosphere, and water.

5.5 Food, Biosphere & Water

5.5.1 Agriculture and Food Systems

One of the greatest challenges of the sustainable development agenda is how to feed a growing population without additional environmental degradation and deforestation, while maintaining biodiversity, ecosystem services, and water resources, and providing climate mitigation through the provision of carbon sinks.

Agriculture clearly needs to become more efficient in new and sustainably "smart" ways. At the same time, food waste needs to be minimized or eliminated. In affluent societies especially, food waste is a major challenge. Roughly one third of the food produced in the world for human consumption every year, amounting to approximately 1.3 billion tons, gets lost or wasted. Industrialized and developing countries dissipate roughly the same quantities of food (670 and 630 million tons respectively). Food losses and waste amount to roughly US$680 billion in industrialized countries and US$310 billion in developing countries. Every year, consumers in rich countries waste almost as much food (222 million tons) as the entire net food production of sub-Saharan Africa (230 million tons; see Gustavsson et al., 2011).

Technology-driven precision agriculture, which combines geomorphology, satellite imagery, global positioning, and smart sensors, enables enormous efficiency and productivity increases. Taken together, these technologies provide farmers with a decision support system, based in real time, for whole farm management. This allows farmers to optimize returns while minimizing resource inputs. GPS-enabled autonomous farm machinery can operate 24/7, reducing labor inputs and minimizing planting and harvesting costs, and even determining optimal harvest conditions based on plant characteristics measured in the field. Smart sensors, often using drone technology, can measure soil and plant characteristics (moisture content, nutrient loads, organic matter, trace elements), thereby enabling more efficient use of fertilizers, pesticides, and water.

However, precision agriculture does not call into question pesticide and herbicide use. It works by refining current practices and does not encourage the exploration of alternatives. This is what scientists call "technological lock-in" (Reboud & Bohan, 2019). It does not prepare us for farming that incorporates new, more ecological or sustainable practices, nor for the development of more sustainable systems richer in biodiversity and higher in resilience.

A variety of biodiversity-based land management techniques can be used in "working lands," including agroforestry, silvopasture, diversified farming, and ecosystem-based forest management, to ensure sustainable production of food and fiber (Kremen & Merenlender, 2018). The Digital Revolution can leverage these approaches. Measurements of system performance across all the dimensions of sustainability would enable the transition to holistic agriculture (Figure 28). The Digital Revolution can enable us to appreciate aspects of a system that we know are important, but which we currently do not properly recognize and value but definitely would once they are gone (Reboud & Bohan, 2019).

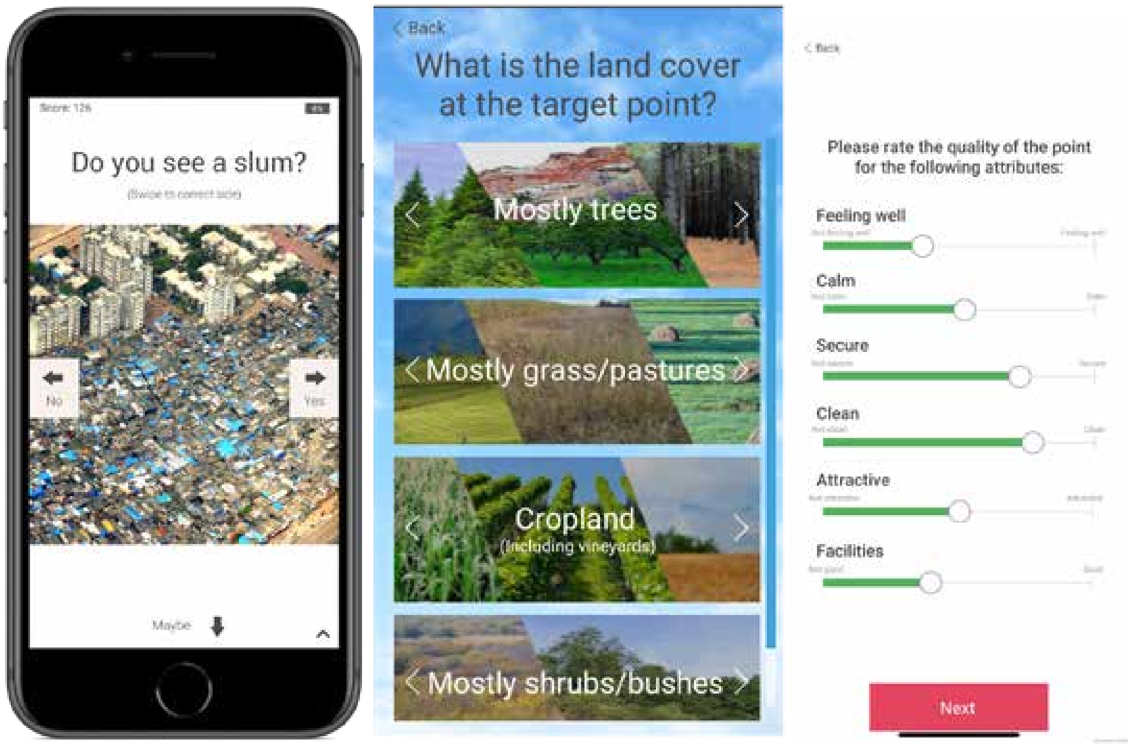

Figure 28. Digital technologies can support citizen science for SDG monitoring and implementation. Earth observation and land use validation apps help investigate and reduce the uncertainties in global land cover data via in situ volunteered geographical data collection through crowdsourcing. From left to right: “Help science by sorting pictures in Picture Pile”. Source: www.geo-wiki.org; “Select the land cover type for a point in FotoQuest Go”. Source: www.fotoquest-go.org; “Find your perfect spot with City Oases”. Source: www.cityoases.eu.

Development of higher yielding, pest-resistant plant varieties that are suited to a wide range of environmental conditions will be required. The role of biotechnology in crop development has been the subject of debate, and widespread moratoria, for decades. Digitalization technologies will further escalate the controversies with the emergence of synthetic biology. However, it is hard to imagine a scenario in which these genetically modified crops do not in one form or another become part of the solution. Yet, it is equally hard to imagine a scenario in which these genetically modified crops have not been tested in new forms to counterbalance various risks. In this way, totally new techno-bio-social-cultural solutions will need to be developed; at the same time, societal acceptance of these solutions will need to be secured in order for these innovations to be implemented.

A possibly more acceptable future approach utilizes synthetic biology and targeted genetic technologies, such as CRISPR-enabled gene editing (clustered-regularly-interspaced-short-palindromic-repeats technology is a simple, powerful tool for editing genomes). This could transform traditional agriculture, create new laboratory farming practices, and help find new ways to leverage complementary agro-ecological approaches (Batra, 2018; Biotechnology Inovation Organization, 2019; Mackelprang, 2018).

These tools have revolutionized biological science and there are no visible limits to their full potential. They are likely to transform genetically modified organisms and create new organisms with heritable traits that nature would have never been able to produce. These tools could enable us to cure cancer and to create laboratory plants and animals. They could transform traditional agriculture, create new laboratory farming practices, and help find new ways to leverage sustainable agriculture, even if they are not “organic” or “ecological” in the strict sense, by leveraging our capacity to enhance the natural biodiversity of ecosystems with hybrid approaches.

Fully automated high-intensity glasshouse agriculture has been shown to dramatically increase crop yields while decreasing water, pesticide, and fertilizer use (on a per kilogram produced basis; see, e.g., Smith, 2011). However, they are big energy consumers, which calls for large efficiency improvements.

Arguably, the world could feed the projected population without radical changes to current agricultural practices if food waste can be minimized or eliminated. Digital technologies will contribute to minimizing these losses through increased efficiencies in supply chains, better shipping and transit systems, and improved refrigeration. Even simple technologies, such as mobile apps (e.g., Flashfood,[11] Food Rescue US,[12] No Food Waste[13]) can facilitate more efficient distribution of food to those in need, ensuring that food that would otherwise be wasted can play a significant role.

Advances in food manufacturing, through 3D printing and "artificial" synthetic foodstuffs, has the potential to relieve pressure on conventional agriculture, particularly large-scale animal grazing. Biorefineries already exist for the manufacture of meat and vegetable substitutes. Overcoming the public perception of quality and health risks of these alternative food sources will be a challenge. "Vertical farms" or "city lab farms" are part of the Digital Revolution, since they are built on highly automated computer-controlled platforms and use LED lightening, automated irrigation, temperature controls, monitoring, and nutrients administration (Crawford, 2018). The produce is close to consumers, long-distance transport is avoided, and carbon emissions reduced, and they also avoid the drawbacks caused by pest controls, nitrification byproducts (nitrates and nitrous oxides), and stormwater runoff. Urban lab farms also increase the natural capital of cities. Although they will never substitute farming, such farms could provide a significant contribution. Moreover, they would certainly contribute to making cities more diverse, interesting, and greener; if city lab farms team up with schools, they could also enrich the educational curricula through introductory courses in biology and agriculture. However, a cautious view is that lab farms will never be able to provide a significant amount of food. They are expensive to build, use a lot of energy for lighting and climate control, and are more expensive than standard farming (Foley, 2018).

Technology can also enhance food traceability, strengthening the role of certification and agreements that aim for environmentally and socially just agricultural production and waste management.[14] The Digital Revolution can enable a just transformation of agricultural and food systems, ending the frequent trend of extreme land concentration in the hands of a few actors. It could enhance governments and the capacity of NGOs' extension and outreach programs to reach multiple scales of farming and agroforestry activities. To help such programs, digitalization can disseminate information and provide support networks with access to advice and knowledge-intensive inputs. The use of networking, virtual and augmented realities (Bailenson, 2018), and games[15] could make a significant contribute to this (see also Box 6).

11 https://www.flashfood.com/

12 https://foodrescue.us

13 https://www.nofoodwaste.in/

14 https://trase.earth/

15 https://gamesforsustainability.org/

5.5.2 Forest Conservation and Restoration

Forests play an important role in the provision of ecosystem services and the mitigation of climate change. Significantly, more forest cover is lost through clearing for agriculture than from forest harvesting for timber. It is hoped that the further development of synthetic building materials and paper will reduce the demand on forest products, and intensification of agriculture should reduce the rates of forest clearing, while novel technologies support monitoring and protection of forest areas. One of the roles of the emerging Digital Revolution is to conserve and restore nature; this will involve leveraging the value of standing forests in the face of other economic uses, such as agriculture (Nobre et al., 2016; Watson et al., 2018).

For example, an innovative program is already under discussion in the Brazilian Amazon to apply new high tech to the industrial use of biodiversity. The "Amazonia Third Way/Amazonia 4.0" (Nobre et al., 2016) aims at developing a socially inclusive, biodiversity-driven "green economy" by harnessing nature's value through physical, digital, and biological technologies. Such technologies increasingly and profitably harness biological and biomimetic assets across many industries, from pharmaceuticals to energy, food, cosmetics, materials, and mobility. A key component of this program is the "Amazonian Creative Labs,"[16] which is designed to generate sustainable high-tech solutions, in collaboration with Amazonian people and based on their eco-systemic resources. The objective is to enable leapfrogging from extractive and low-income, low-value-added agriculture models to state-of-the-art solutions that add value to existing biodiversity-based value chains by exploring new models, including those involving high-end genomics. The success of such initiatives could contribute to several SDGs, provide value for the standing forest, and benefit the local economy.

The Digital Revolution could also help the diffusion of knowledge about established and very successful restoration projects, such as the Instituto Terra[17] and the Working Landscapes (Kremen & Merenlender, 2018) initiatives. Biodiversity-based land management practices are more knowledge than technology intensive. They are well adapted to empower local communities to manage their natural resources (Kremen & Merenlender, 2018). The impact could be high across regions where the full transition to industrial clearing and exploitation of forests has not yet happened, as well as in regions where the consequences of unsustainable exploitation have manifested and restoration offers a solution. In addition

16 https://believe.earth/en/carlos-nobre-the-amazonian-intelligence/

17 http://www.institutoterra.org/eng/index.php

to the ecological impact of sustainable practices, these initiatives can provide employment.

Other digital technologies that are emerging as potentially useful tools for management of natural resources include those of extended reality (XR), which is an umbrella concept encompassing technologies of varying degrees of immersion, such as augmented reality and virtual reality. The technologies themselves are not new, but their popularity has grown exponentially since virtual reality (VR) went mainstream in 2016. Somewhat slower to take off, augmented reality (AR) is expected to be the dominating extended reality technology from the 2020s. The two technologies offer exciting yet different possibilities for natural resource management.

Augmented reality technologies, especially light detection and ranging (LiDAR), are bridging the gap between the global scale of climate change and the local scale at which the changes in the biosphere can be measured. Laser scanning data is processed to render 3D reconstructions of topography, terrain, and vegetation structure. Global trends can be correlated with observed changes in biodiversity at the scale where it matters (typically a resolution of 5 meters) throughout landscapes. An early study demonstrated

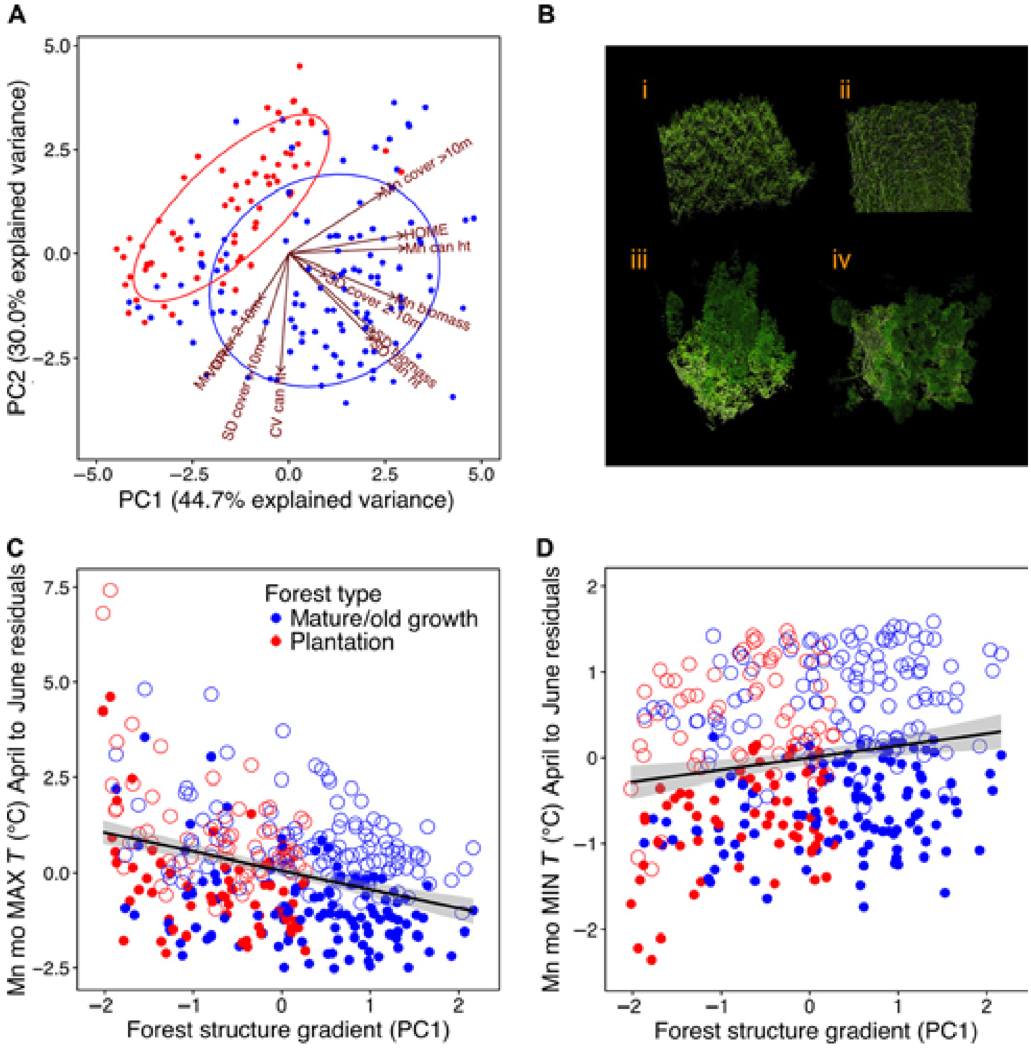

Figure 29. Differences in microclimate conditions across a gradient in forest structure. (A) Principal components analysis (PCA) showing how vegetation structure metrics differ between mature/old-growth forest sites and plantations. The ellipses represent 68% of the data, assuming a normal distribution in each category (plantation and mature/old-growth). (B) Three-dimensional LiDAR-generated images of plantation forests [(i) side view; (ii) overhead view] and old-growth forests [(iii) side view; (iv) overhead view] at the Andrews Forest. (C and D) Results from generalized linear mixed models show the modeled relationship between forest structure [PC1, the first component of a PCA on forest structure variables (A)] and the residuals from an elevation-only model of mean monthly maximum from April to June (C) and mean monthly minimum from April to June (D) after accounting for the effects of elevation. Closed circles represent 2012 and open circles represent 2013. Maximum monthly temperatures (C) decreased by 2.5°C (95% confidence interval, 1.7° to 3.2°C) and observed minimum temperatures (D) increased by 0.7°C (0.3° to 1.1°C) across the observed structure gradient from plantation to old-growth forest. Source: Frey et al. (2016).

that individual LiDAR metrics effectively distinguished between plantation sites and mature, old-growth forest sites (Frey et al., 2016), mapping the topography and vegetation structure in a way that correlates with microclimate conditions (Figure 29). LiDAR provides data to compute 3D reconstructions of the surface of the Earth, enabling the characterization of habitats, water cycles, carbon cycles, and changes in biodiversity. This precise information enables us to build three-dimensional time-dependent analyses and forecasts of physical parameters using models built from first principles, and to model the surface of the Earth as a system linked to climate and oceans. As oceans have traditionally been of critical national security importance for geopolitical and commercial reasons, the deployment of advanced digital technologies has been more integrated and coherent than in agriculture and ecology. We discuss this further in the next section as a case study.

In virtual reality, the use of a headset, often accompanied by headphones, immerses the user fully in the visual presentation, which can be in the form of video, photos or computer-generated imagery (CGI). Virtual reality has been found to elicit feelings of empathy in the viewers (Herrera et al., 2018), to facilitate learning (Bailenson, 2018), and to impact behaviors (Bailey et al., 2015). However, different types of virtual reality experiences, such as different production formats and degrees of interactivity, have different impacts on the viewer. Moreover, only a limited number of studies have been undertaken to understand the lasting effects of virtual reality experiences in general and on natural resource management in particular. Possible applications are virtual tourism in parks, and the promotion of knowledge about nature and wild animals, thereby avoiding the carbon emissions of long-distance travel.

In augmented reality, digital 3D objects are added to real-time video renders and presented on devices such as mobile phones or tablets. By being presented on a screen, augmented reality invites real-time, onsite dialogues. The 3D elements can be triggered by a designated real-world landscape, either indoors or outdoors, or by props such as mats. The technology can thus be useful for creating and communicating visions of partially or fully imagined areas or elements. An early example of using augmented reality technology for visualizing environmental data was presented by Ghadirian and Bishop (2002). In more recent examples, augmented reality has been used to educate people on the importance of animal conservation and on park landscapes. In the continued development of AR, and indeed virtual reality, we may see how applications become better connected to other digital elements,

Table 3. Novel developments in ocean technology

Observation technology	• automated observations of subsurface ocean temperature, salinity, currents, and increasingly biochemical parameters by the ARGO system* autonomous and automatic underwater vehicles to observe seafloors, underwater structures, and lifeforms • new hydroacoustic and optical sensors increase the ability to automatically observe phyto-, zooplankton, and fish • platooning and swarms of autonomous underwater vehicles • space-based remote observation of these parameters and others (e.g., surface waves) on rapid time scales
Computer-based modeling, analysis, and exploration	• three-dimensional time-dependent analyses and forecasts of physical parameters using models built from first principles • analyses and forecasts of biogeochemical parameters (e.g., phytoplankton) using emerging observational capabilities combined with physical parameters listed above • immersive and 3D visualization for computer-aided exploration
Assistive methods and tools for model and analysis implementation	• specialized languages for modeling and automatic code generation allow integration of knowledge across different disciplines • automation and documentation of scientific workflows through executable notebooks support the digitalization of workflows
Data lifecycle support infrastructure and methods	• decentralized cloud data storage • digitalization of data processing and storage to foster traceability of scientific results • adoption of FAIR principles** improve access to and rescue of scientific data

*Broad-scale global array of temperature/salinity profiling floats, known as ARGO: http://www.argo.ucsd.edu/About_Argo.html.

**https://www.go-fair.org/fair-principles/

such as sensors, to enable analysis and visualization of real-time data.

The Digital Revolution in information and communication technology could help provide the tools to inform the public about the positive attributes of new technologies and to engage their support ex ante. Information and communication technology can underpin the proper identification and traceability of products, whether produced by traditional farming, novel high-tech and hybrid sustainable practices, or organic methods. A well-informed public could shift consumption choices toward new, high-tech, low-impact or sustainable production, which would decrease our industrial footprint.

5.5.3 The Digital Ocean

The ocean, long a mysterious and foreboding realm, is becoming ever more transparent and accessible with the advent of digitalization. This trend promises great advantages for society, as well as associated challenges. Notable developments are listed in Table 3 (see also Figure 30).

These developments in digitalization have direct practical application in science, economics, and education, such as for ship routing and the associated impacts on the economics of the marine transportation system. Greater efficiencies in this arena will increasingly be reflected in the prices of products on store shelves, a large and growing fraction of which arrive from far flung corners of the globe.

Immersive computer-aided exploration enables exploration of underwater habitats and the seafloors. This exploration is interactively augmented by contextualized information, like salinity and temperature, providing underwater access to more scientists (Figure 30). Immersive technology, such as 3D and 2D graphics, supports education, outreach, and consulting, provides customized and interactive visualizations for stakeholders to support the understanding of natural processes, and accelerates their decision making by enabling instant feedback on their scenarios.

Software engineering methods help scientists keep track of the codes and code changes in their models and analyses. This supports the quality, reuse, and integration of the models, which in turn enables users to reduce costs and reaction times when confronted by new challenges because they are able to provide on-time assessments and solutions (Figure 31). Automation and documentation of scientific workflows complement this advantage, because executable notebooks, like Jupyter, make scientific work more transparent and transferable. This has two major benefits: (i) it improves acceptance of results in the community and beyond, and (ii) it reduces the time it takes to apply specific workflows to new data. These

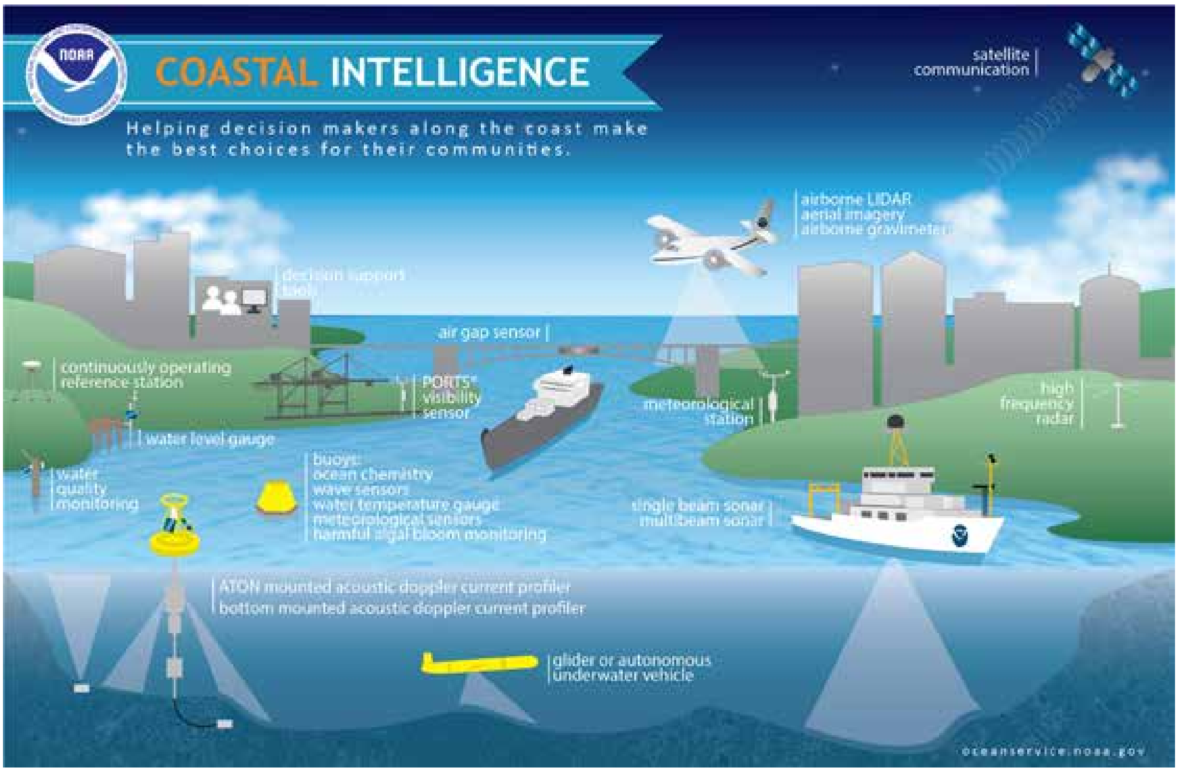

Figure 30. Coastal Intelligence: Digital acquisition of data on many ocean variables with advanced approaches. Source: NOAA (www.oceanservice.noaa.gov).

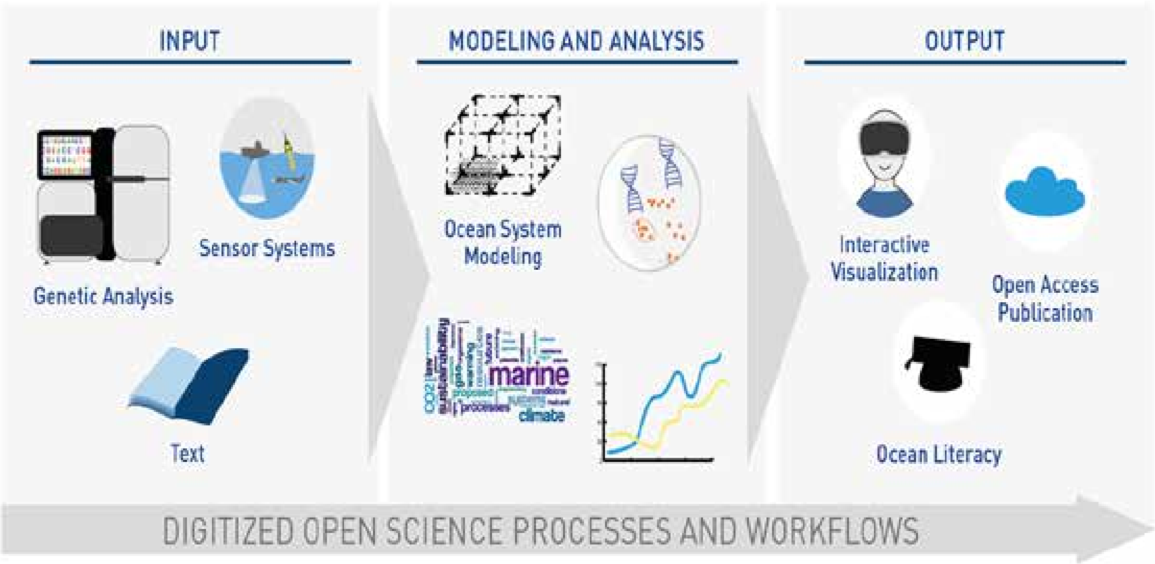

Figure 31. Digitized open science processes and workflows. Source: Tine Pape/©EXC The Future Ocean.

methods therefore support the proliferation of science-based forecasting systems.

Efforts around the data lifecycle and the adoption of the FAIR principles support the decentralized storage of research data and the accessibility of data from any research computer. The lifecycle enables scientists to reuse data, reexamine findings, and show when and how data was modified. This limits fraud and, therefore, increases confidence in observation data and results.

Other developments include the rapidly improving ability to forecast fish behavior and abundance. This has positive implications for efficient management of

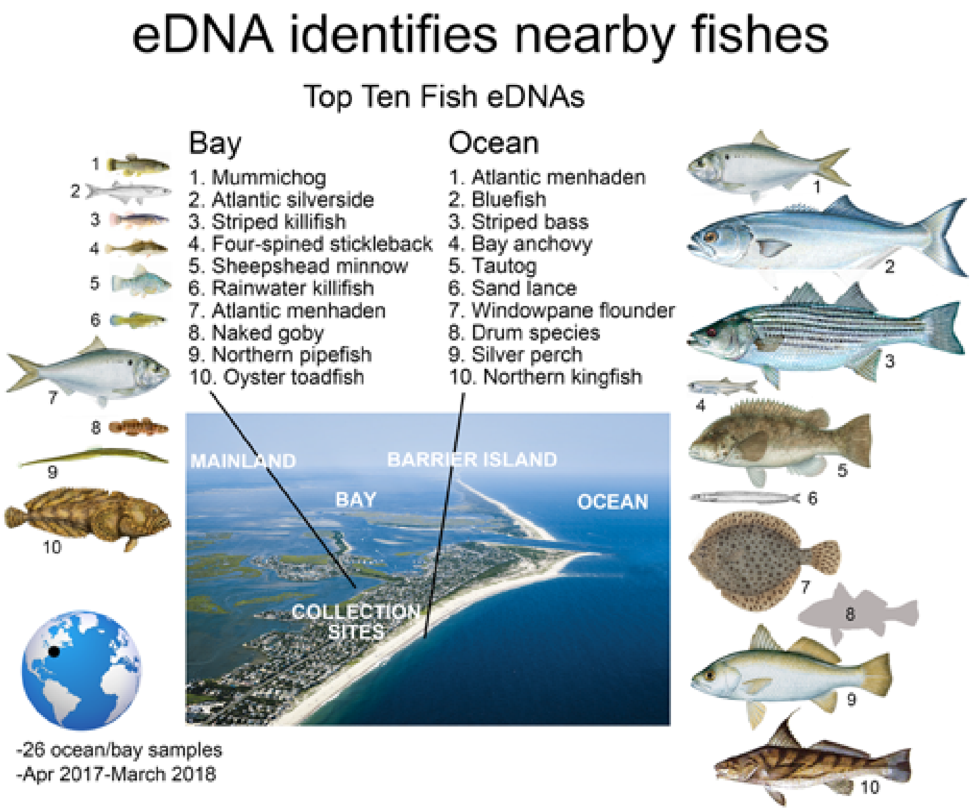

Figure 32. Marine environmental DNA (eDNA) sampled in adjacent ocean and bay habitats shows that DNA stays close to where the species are. Source: Graphic courtsey Mark Stoeckle, The Rockefeller University (https://phe.rockefeller.edu/barcode/blog/nycnj-aquatic-vertebrate-edna-project/).

fisheries and oceans, which also greatly improves the ability to protect sensitive bycatch species like marine mammals, sharks, and seabirds. However, the potential for illegal exploitation of such improved abilities leads to questions of governance. The downside is a higher risk of over-exploitation of the sea and accelerated fish depletion.

Emerging digital technologies promise to bring additional dimensions. DNA barcoding has been shown to be capable of identifying fish sold in restaurants and thus to expose fraudulent substitution of less expensive species or the sale of restricted species. This same capability can be used to identify sea food, which is wasted, thereby providing information useful for optimizing the supply chain. Further, emerging environmental DNA analysis techniques promise to detect the presence and absence of fish and other species based on tissue shed as fish swim through the water, and this may lead to remote sensing of fish abundance (Figure 32). The advent of space-based radars holds the promise of tracking ships engaging in illegal, unreported, and unregulated fishing, even when ship operators turn off mandatory automated identification systems. All of these have immediate and emerging implications for global food security and promise to bring objective information to bear on governance of the high seas.

As nations increasingly compete for resources (e.g., minerals, oil, fish) and rights (e.g., passage) in a changing world, national security is also affected by the increasingly transparent digital ocean. For example, nations large and small operate fleets of submarines to patrol regions of economic interest, and these operations are increasingly dependent on advanced digital depictions of the environment. The deployment and use of hypersonic torpedo-like devices is in its infancy, but it parallels the development of controllable missiles decades ago, with all of the concomitant issues of governance and social acceptability. Dimensions of concern include maritime safety issues and cybersecurity, as ships are increasingly networked or autonomous and automatized, which increases their susceptibility to hacking.

A final example of broad impacts emerging from the digitalization of the ocean comes from space-based remote sensing of ocean salinity. Although still in its infancy, time-delayed significant correlation between patterns of high salinity in the ocean basins and increased rainfall over land has been observed. This leads to the possibility of significantly improved seasonal climate forecasts, which in turn have implications for agriculture, severe weather, and related economic factors (Schmitt, 2017). More real-time information regarding fish species, fishing practices, and sustainability may help consumers makes choices that reinforce the SDGs (see sections 5.3.1).

5.5.4 Water

The deployment of digital technologies has the potential to deliver significant outcomes in the water sector. Virtual representation of the water system will enable situational awareness or near-real-time surface water flow and quality monitoring, as well as monitoring of groundwater levels (recharge vs. abstractions) and quality assessment and control. These benefits promise solutions to many of the challenges and environmental externalities faced by the sector (Figure 33). The water sector still lags behind other industries in integrating new, smart technologies in the water ecosystem. But digitalization is expected to increase with the adoption

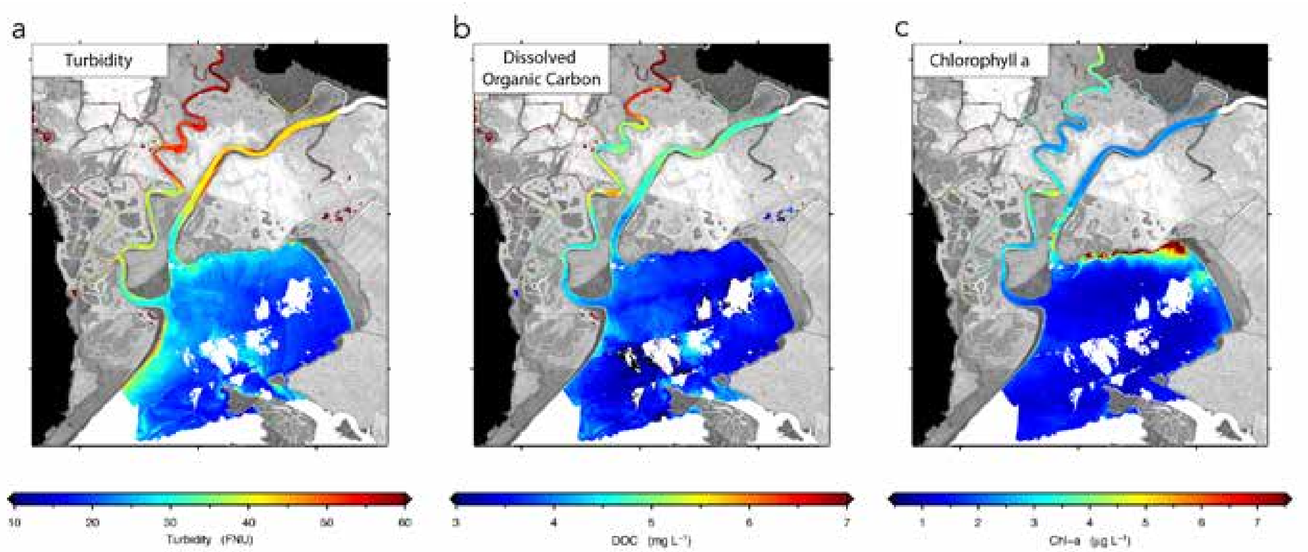

Figure 33. Maps of (a) turbidity (water clarity), (b) dissolved organic carbon, and (c) chlorophyll-a in the San Francisco Bay-Delta Estuary's Grizzly Bay and Suisun Marsh in April 2014, derived from remote-sensing reflectance data from NASA's airborne Portable Remote Imaging Spectrometer (PRISM) instrument. Source: NASA/JPL-Caltech (2016).

of advanced technological capabilities, improvements in the collection capabilities of information from remote devices, and developments in correlating that information across diverse systems.

Digitalization has the power to help water and wastewater utilities address many of the challenges they face. This includes extending the life of aging assets; reducing leakages, attacks, or other abnormalities in the distribution network; improving water quality monitoring, service levels, and reliability of supply; promoting water conservation; and increasing revenue through operational efficiencies. Successes can be recorded in improvements in event response times, increases in work reutilization, and even reductions in energy use across the water treatment and distribution network. Another likely area of progress in the foreseeable future is video imaging and pattern recognition enabled by cognitive or augmented technologies. These technologies will be particularly applicable to real-time water quality monitoring, leak detection, and asset assessment management in general. The wealth of data will enable service providers to use predictive analytics to spot problems and proactively send crews out to prevent or solve problems, such as by replacing water distribution lines long before small leaks become catastrophic events.

Digitalization will improve wastewater treatment and reuse, distinguishing between green, blue, and gray water, and understanding sources and types of pollution. In apartment houses, digitalization could support the proliferation of onsite treatment, reuse of wastewater – especially in new high-rise buildings – and gray water recycling.

Risk analysis and disaster preparedness are also areas on the rise. Water utilities and municipal authorities are exploring new ways to become more resilient (Figure 34). For example, IBM has partnered with the UN Office for Disaster Risk Reduction (UNDRR) to publish a Disaster Resiliency Scorecard,[18] which over 200 cities worldwide have used to assess several aspects critical to timely and efficient anticipation, mitigation, preparation, and recovery in relation to the effects of a hazard. This initiative covers policy and planning, and the engineering, organizational, financial, social, and environmental aspects of disaster resilience. Information flows between actors and within actor networks, both in top-down (through early warning systems) and bottom-up (through citizen science and citizen observatories) directions, have proven critical to speed up responses across all phases of the disaster risk cycle (preparedness, mitigation, recovery) (Buytaert et al., 2014). Digitalization and information technologies are already playing, and will increasingly play, an essential role in enabling real-time information flows and early warning to reduce impacts from water-related risks and to build resilience and adaptation to climate change (Giordano et al., 2017).

Private sector infrastructure delivery is a promising space to examine best practices and lessons learned. In this area, advances in the energy sector are worthy of replication. Water utilities can benefit from the lessons learned and the established best practices. The potential for leapfrogging is real, given that technology

18 https://www.unisdr.org/campaign/resilientcities/home/toolkit

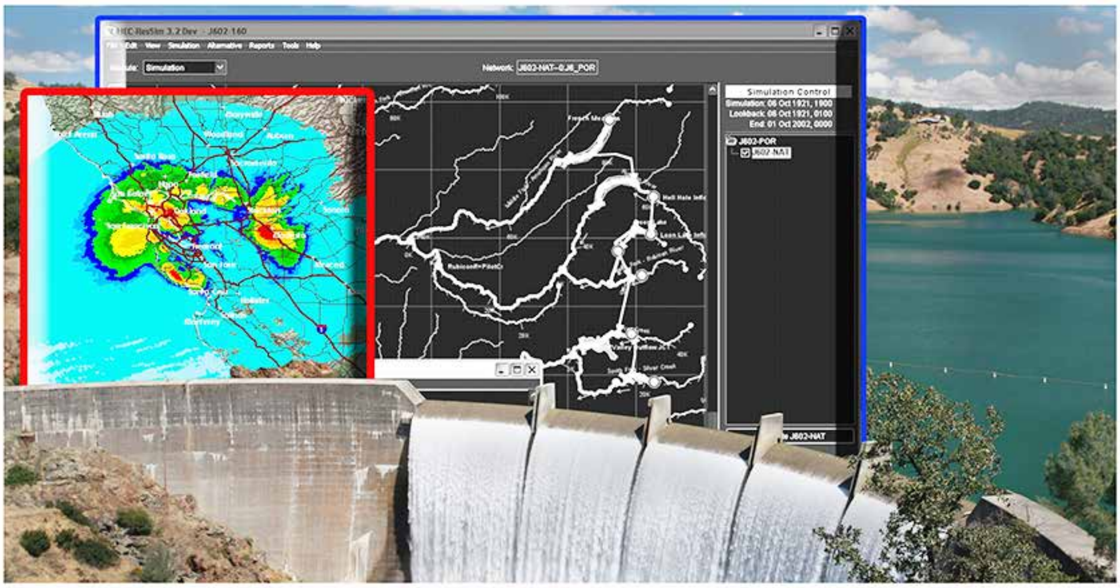

Figure 34. Advanced weather and channel flow data shared via instant communications between water management agencies is critical to California's Central Valley during an active flood season. Source: US Army Corps of Engineers (2013).

has evolved and prices for smart devices have decreased while their functionality has increased.

Green innovation in agriculture is another emerging area in which digitalization is making huge progress. From a water perspective, weather data can be used to predict the amount of rain, so farmers can better manage the application of farm chemicals to minimize pollution of aquifers and surface water systems used as drinking-water sources. Meanwhile, smart meters, onsite and remote sensors, and satellite data connected to mobile devices allow for real-time monitoring of crop water requirements and optimal irrigation demands. On the supply side, remote tele-control systems and efficient irrigation technologies enable farmers to control and optimize the quantity and timing of water application, while minimizing the energy consumption trade-offs of pressurized irrigation in both rural and urban agricultural settings (Germer et al., 2011; Ruiz-Garcia et al., 2009).

In addition, the application of blockchain technology is another promising area. For instance, blockchain could mediate competing demands on water (households, industry, energy generation, agriculture, nature) to avoid overuse, and the application of blockchain credits for proving efficiency measures could address the problem of drought. If utilities can prove that they are being more efficient, they could earn blockchain credits. This could create a market with the shifting of water and drought situations, thereby effecting real change in behaviors because there will be a monetary reward for greater efficiency.

Digitalization will strengthen the participation of local communities in improving water and wastewater management. But the Digital Revolution will continue to place a significant demand on high educational attainments and skills. Utilities, government agencies, and local administrative authorities will struggle to keep up with the talent demands resulting from digitalization. This will continue to be a challenge in countries where literacy levels are still very low and the capacity of most people to make informed choices from smart devices is still largely inadequate. In Africa, for example, the development of smart cities will hinge on technological readiness, and on the human and institutional capacity of its cities to produce and handle big data. In more advanced societies, customer expectations around sustainability are driving behavioral changes in traditional utility practices. In some places, civil society (consumers) already participates in water conservation and wastewater reuse. It can be expected that, as utilities digitize, more can be expected from civil society in the areas of innovation and smarter decision making about the use and reuse of water.

Despite anticipation of the many promising applications of digital data, the challenges are still very real. In particular, the reluctance of public institutions to address concerns about data security is a problem. Cybersecurity is already a concern today and the risk is increasing. Historically, the water utility control systems were not designed with security in mind, so network intrusion is also an increasing concern. There are threats to the critical control systems, especially those that control water flows, such as treatment works and dams.

But perhaps the real challenge over the coming decades for utilities lies in setting the foundation for utilities to begin applying data science and augmented intelligence techniques to tangible business problems. The water sector still lags behind others, especially the infrastructure sectors such as energy, transport, and buildings, in integrating new, smart technologies into the whole water ecosystem. In many African countries, new technologies like augmented intelligence, cloud

Box 12. Narrative for 2050: Smart Cities, Decent Housing, Mobility, Sustainable Infrastructure, Pollution

By mid-century, cities neutralize their carbon footprints through recycling and “urban mining”. Cities are a combination of compact mixed-use areas of living and working spaces, and they are environmentally and socially safe. Digital progress has changed the nature of urbanization, with more people in remote locations able to connect to the dynamism offered by cities, leading to increased integration of the urban hinterland (Svedin & Liljenström, 2018). The interplay between what is today regarded as “urban” and what is not (sometimes referred to as “rural”) will have to become more systemically strengthened and, in many places, merged as vast regional “agglomerations” of patches that combine urban and rural functions over a large area (Svedin & Liljenström, 2018). Previously “informal” settlements and slums are now livable settlements. Global and regional hubs are more connected, and the earlier tendencies of tele-connections between major mega-cities will have grown and consolidated in many ways that were not even envisaged around 2020. Housing is no longer considered a purely private shelter; rather, it has become an essential component of a larger social system giving people better opportunities to connect with each other. Transport solutions are more integrated, systemic, autonomous, emissions-free, and shared. Longer-distance travel is undertaken largely by a combination of fast rail, magnetic levitation transport, and low- or zero-emission aircraft.

computing, and sensor technology are beyond the reach of many water and wastewater utilities, which are still caught up in collecting and analyzing information in reports that are usually presented on paper.

5.6 Smart Cities

5.6.1 Mobility

The major change in individual transport during the Industrial Revolution was the replacement of the horse and carriage by motor vehicles. The other fundamental change was the invention of the elevator, which made dense city centers possible. Initially requiring "drivers," elevators later became the first "self-navigating" vehicles in response to a passenger's floor choice.

In the case of automobiles, many propulsion technologies initially competed, ranging from steam and electricity with on-board storage, to the internal combustion engine. The first vehicles resembled carriages, but within a decade radical divergence had occurred. Cars became made from steel, and eventually the chassis was replaced by a unit body. Innovation continued, including automatic transmission, electronic engines and car management, active emissions controls, and many safety features, such as seat belts, crash zones, and air bags. Many creature comforts were introduced, including power steering and braking, air conditioning, entertainment systems, navigation, Internet, power windows, and seats. Although the efficiency of the vehicles improved, fuel consumption improvements were modest because of increased weight and on-board power needs. Great improvements have been made with regards to regulations of air pollutants and greenhouse gas emissions.

In most countries, the substitution of the horse and carriage for cars lasted about 30 years. The process was essentially completed in the USA by the 1930s, and in most other industrialized countries soon thereafter. Most developed economies now have car ownership rates of close to one car for every two people. This is not the case in many developing parts of the world where the process is often incomplete and ongoing.

Globally, there were an estimated 1.37 billion vehicles in operation (VIO) in 2017, a 4.1% increase from 2016 (Wards, 2017). Much of the recent growth came in developing regions where a rising middle class expanded the market (Figure 35). While the accelerated growth of China's new-vehicle sales tempered in 2017, rising demand for used vehicles there helped keep the VIO growth above 11% at a total of 215.6 million. Though still at a high of almost 6 persons-per-vehicle ratio compared to 5.5 on average for the world. At the current growth rate, there will be some 3.4 billion VIO by 2030 globally for an estimated population of about 8.5 billion people (Lutz et al., 2018), which is very close to one car per two people. With the current technology, this would imply an increase of fuel needs as well as negative environmental externalities such as air pollution by a factor of 2.4 compared to today. Congestion and the need for parking spaces need to be considered, as too should the risk that many

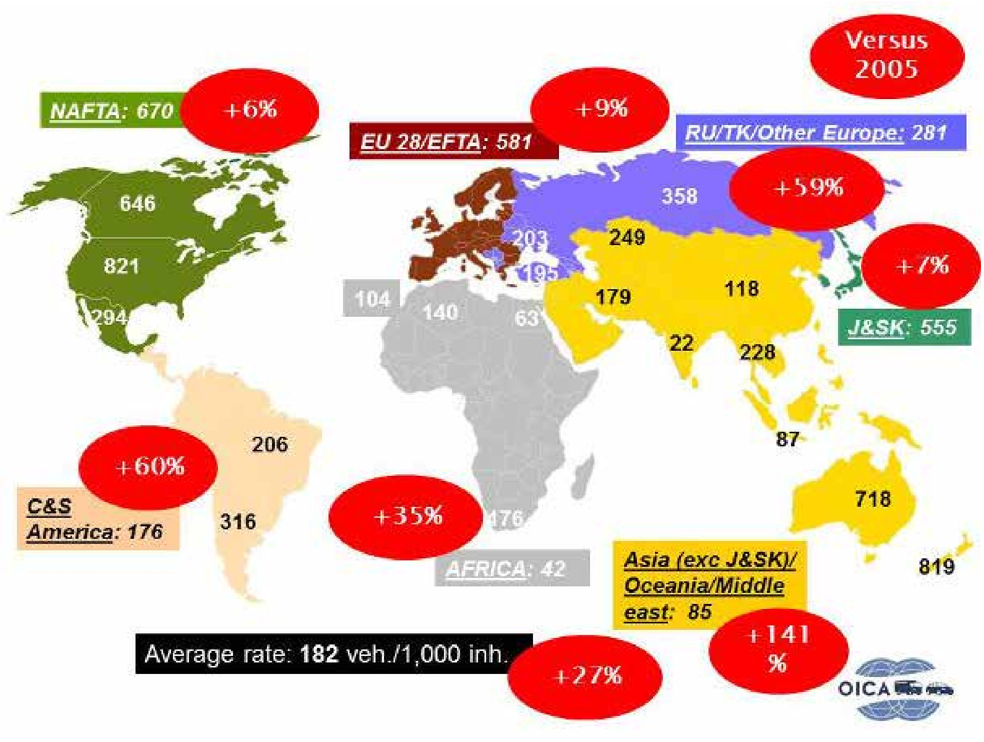

Figure 35. Motorization rates for 2015 and increase since 2005 across regions worldwide. Source: OICA.

settlements will become environments for cars rather than for people. Already the parking area in Los Angeles is greater than the total land area of New York (Woods Bagot 2018). At the same time, congestion and pollution problems may limit the increase of vehicles in the next decade.

Electric and plug-in hybrid cars and buses are a great hope for reducing the environmental impacts of vehicles – assuming, of course, that the required electricity is sustainably produced without air pollution and greenhouse gas emissions. In 2016, the share of electric vehicles (EVs) in new sales globally reached 1% for the first time, and it passed the 2% mark in 2018. This translates to a stock of above three million cars or 0.4% of the total stock (Bunsen et al., 2018). Hydrogen propulsion also offers great potential for reducing emissions, although the industry is in its infancy. It might be more promising for trucks than for cars, mainly due to the high cost of fuel cells. Infrastructure needs to be built up and costs need to be lowered in the hydrogen supply chain to make this fuel source attractive.

Several countries and regions have effective incentives for increasing the fleet of zero-emissions vehicles. In Norway, for example, 40% of new vehicles are electric or hybrid (Bunsen et al., 2018). Some of the incentives include rebates on new purchases, waivers from congestion and road taxes, free charging, lower parking charges, and the right to use the "fast" lanes reserved for public transport or multiple occupancy vehicles.

There are indications that attitudes toward zero-emissions vehicles are changing. This is illustrated by the fact that virtually every manufacturer has electric and plug-in hybrid vehicles in their development programs. A recent survey indicates that most consumers are willing to pay more for alternative propulsion vehicles, with improved fuel consumption cited as the main reason for considering a battery-electric or plug-in hybrid vehicle. Significantly, 80% of people aged 18–34 say they would pay more for a vehicle that is powered by something other than a traditional internal combustion engine. Those with only high-school education or below were less willing (49%) than people with an undergraduate degree (71%) or a graduate degree (85%) to pay more for an alternative propulsion vehicle (Jolley, s.a.). In other words, the better educated and the younger the individual, the more likely it is that he or she would purchase a zero-emissions vehicle. This is an early indication that the replacement of conventional by zero-emissions vehicle could be at least as swift as the replacement of horses, meaning that by 2050 most vehicles in urban and peri-urban areas would be zero emissions.

This, or even more pervasive revolutionary developments in mobility, could occur over the next three decades. Artificial intelligence, big data, and additive manufacturing could combine to enable autonomous driving vehicles, provided that the necessary underlying infrastructure, institutional, legal, and regulatory processes are in place. Autonomous vehicles need to be able to deal with all possible contingencies by communicating among themselves, with information exchanged with the infrastructure, manufacturers, services such as the police, and, of course, with the passengers. This will require big data and immense computing power to ensure that quick decisions are made in difficult situations. Current prototypes and cars on the road can master many of these challenges, but they are not yet fully autonomous as they require a driver behind the wheel when critical situations occur. It would be a quantum leap to achieve full autonomy for vehicles without human intervention in difficult situations. It is estimated that an autonomous vehicle would generate four terabytes of data in an hour and a half, the average daily time of a car in operation (Winter, 2017). For example, BMW has announced development of a digital platform for autonomous vehicles with storage capacity of 230 petabytes (BMW Group, 2019). The emergence of autonomous vehicles would bring back some of the intelligence of the horse that was lost when they were substituted by cars – namely, horses can go home alone! The introduction of self-navigating vehicles should unfold with a focus on the opportunity this new technology presents to improve public welfare and safety, and it should come with an awareness that realization of the opportunities depends on positive public engagement. In Japan, for example, autonomous driving is expected to play a major role in the design of mobility systems in an aging society by local governments, railway companies and car makers and information-technology companies.

A very simplified thought experiment: Current vehicles achieve average speeds of some 50 kilometers per hour and are used on average for about one hour each day. This means that 1.4 billion VIO travel about 70 billion kilometers per day. In contrast, an autonomous vehicle could be operated closer to 24/7 rather than for one hour per day. If the productive driving, namely with passengers, is 10 hours per day, then there would be 10 times fewer vehicles. In other words, 140 million vehicles would provide the same service (provided that private car ownership is substituted by shared autonomous vehicles). So, instead of producing about 100 million vehicles a year, as the industry does today, only about 10 million cars would be produced. This would decrease materials use by a factor of 10, congestion and the need for parking places would be drastically reduced, and, importantly, it would almost eliminate road accidents and deaths (Figure 36). However, this would result in drastic changes to the automotive industry, which currently accounts for approximately 3.5% of US GDP and over

	Reductions (%) in shared mobility scenario compared to status quo			
	vehicle fleet	congestion	mobility costs	CO_2 emissions
Auckland	-95%	-49%	-43%	-54%
Dublin	-98%	-43%	-50%	>-31%*
Helsinki	-96%	-37%	-43%	>-34%*
Lisbon	-97%	-30%	-50%	-62%

** IC vehicle fleets, no electrification*

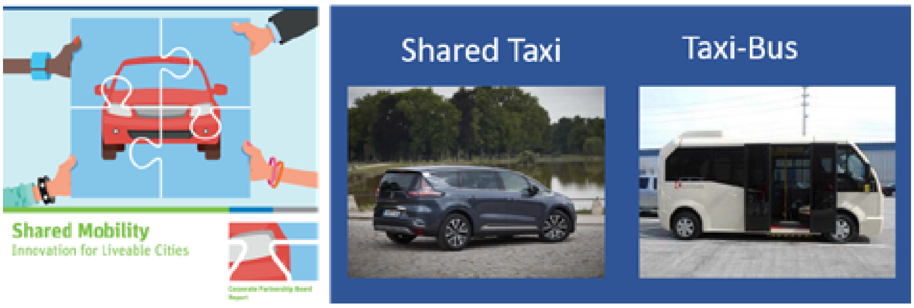

Figure 36. Impact of comprehensive urban shared mobility on vehicle fleets, congestion, mobility costs, and emissions in four example cities, based on detailed big data simulations of trip patterns and an agent-based model of shared mobility coordination. Source: ITF (2019).

20% of all industry revenue in Germany, where nearly 800,000 people constitute the automotive workforce (GTAI, 2018).

Shared mobility models (e.g., Uber, Lyft, Didi Chuxing, 99, Careem, Curb), particularly for private passenger transport, have become ubiquitous from California to New Delhi, challenging both traditional (high-cost) taxi services and public transport. These mobility service business models can be extended into a single comprehensive urban transport service platform that integrates public and private transport, as well as all urban transport vehicles, including buses, cars, scooters, and bicycles (but not high-capacity rail-based systems, such as light rail or metros). ICT could provide consumer information to strengthen the range of available choices and influence consumer decisions (see section 5.6).

The OECD International Transport Forum (2019) has conducted a number of detailed big data simulation studies for four test cities to explore the feasibility and impacts of a comprehensive urban shared mobility model in which all trips are provided by an integrated shared mobility service via a shared taxi and taxi bus fleet. The conclusions from these agent-based simulation models are stark. All urban mobility can be provided at any time and for any trip patterns with only a small percentage of the existing vehicle fleet, drastically reducing traffic congestion, energy use, and mobility costs, while simultaneously lowering emissions even with continued reliance on conventional (internal combustion) vehicle technology. A particular appeal of this shared urban mobility option is that it can be implemented quickly, using existing vehicle fleets. It also offers a particularly attractive option to improve transport options and accessibility for traditionally underserved and disadvantaged segments of society (low-income households without cars, residents of peripheral city suburbs with inadequate public transport service), and it constitutes an attractive, cheap, and convenient alternative to individual car use in densely populated urban areas.

The demand for conventional vehicles is likely to decline in mature markets as younger generations show much less interest in driving themselves, as indicated in ever lower numbers of driver licenses being issued. For example, in Stockholm only 10% of 18-year-olds hold a driver's license (Aretun & Nordbakke, 2014), and there has been a 40% reduction in license applications in the USA. Thus, the transition toward self-navigating vehicles would start with increasing demand for collective transport mass-transit systems. Many manufacturers are responding to the these shared-ownership trends by providing flexible vehicle rental arrangements in urban areas. This kind of radical transformation implies a fundamental change in vehicle ownership toward shared on-demand vehicles. This could be in the form of service-company ownership of vehicles like taxis and other commercial vehicle fleets. This is a powerful trend reflected in the market valuation of mobility companies. For example, whereas BMW is valued at below US$50 billion, Uber is valued at over US$80 billion, which is about the same as the valuation of Volkswagen (Kenwell, 2019).

New business models are likely to emerge. It is also important to note that the tendency of individual choice in family transportation has to be included in the assessment of the aggregated urban situation. In emerging markets, the demand for passenger vehicles is growing and will drive overall sector demand in the coming decades. Another innovative possibility is three-dimensional elevators (based on magnetic levitation; see Ackermann, 2014) as an extension of subways and other forms of integrated and shared mobility; such an innovation could have important implications for how future cities are built.

Today, drones are already self-navigating with minimal "flying" instructions required from the operator. In fact, they have many features of autonomous vehicles in that they monitor their environment to avoid collisions and choose appropriate flight paths consistent with operator instructions, local regulations, and avoidance of danger zones such as airports. There are many drones in design to autonomously carry passengers. Recent initiatives include the plan to take passengers to and from an airport via drone, which Frankfurt and Dubai airports hope to realize within a decade (Chen, 2019).

Electric aircraft are a complementary development. Small, four-passenger electric planes can be purchased today (e.g., from Pipistrel[19]), and manufacturers and designers are working on larger versions. A major challenge is that the current battery technology cannot produce full power for the eight minutes required to reach cruise altitude. Thus, designers are using hydrogen fuel cells to augment battery power. On landing, some energy is recuperated so that batteries recharge. With this innovation, electric aircraft could serve to bring passengers to hub airports. Even long-range aircraft can be fueled by hydrogen, reducing CO2 emissions to zero, assuming the source of energy is carbon free. Some of the most visionary designs include Progress Eagle by Oscar Viñals,[20] which combines a number of advanced technologies to provide long-range travel. It includes solar cells, hydrogen turbines for takeoff, and a large ducted fan propeller for electric drive in cruise and for recuperation on landing. About 40% of the technology required to build the aircraft exists today, and the remaining gap could be closed within a decade or two (Viñals, 2014).

Perhaps the most attractive option for long-distance travel is magnetic levitation (maglev). Such advanced trains are already in service, for example, from Shanghai airport to the city. Japan, which has a dense network of high-speed trains called Shinkansen (Figure 37), is building a maglev train from Tokyo to Nagoya. A complementary development is the Hyperloop,[21] a proposed mode of passenger and freight

19 https://www.pipistrel-aircraft.com/

20 https://www.behance.net/gallery/20804291/AWWAQG-Progress-Eagle-Quantum-Airplane

21 https://hyperloop-one.com/

Figure 37. Top: Maglev train in operation, Japan. Source: Courtsey of JR Tokai. Bottom: Chūō Shinkansen. Yellow line Chūō Shinkansen. Route proposed by JR Central. Light yellow line Chūō Shinkansen route detail is undecided. Red line Yamanashi Test Track. Source: Hisagi - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=15456682.

transportation using maglev technology in evacuated tunnels to reduce friction and achieve velocities comparable to those of aircraft.

In a possibly shared economy of the future, sustainable mobility can become a reality, with integrated mobility and transport systems that include self-navigating vehicles working like swarms to provide flexible, efficient, fast, and zero-emissions services. Such systems may include three-dimensional maglev elevators, maglev trains, self-navigating cars, drones and aircraft, all of them electric. During the Industrial Revolution, the emergence of railways provided infrastructure for emerging urban settlements that evolved along metro lines. Later, the pervasive diffusion of automobiles did the same for newer urban settlements. It is quite possible that the advanced, self-navigating, and organizing mobility and transport systems of the future will do the same for emerging urban centers for the seven or more billion people living in cities around the world in the second half of the century (GEA, 2012).

5.6.2 Smart Spaces, Buildings, and Homes

The Industrial Revolution had a major impact on buildings as well as on cities and the landscape. The growth in productivity and focused production resulted in lower opportunities (and wages) in agriculture, while it increased opportunities in the cities, resulting in migration and sprawling urbanization. This further impacted on culture and society.

The Industrial Revolution created new and abundant building materials, including cast iron, steel, and glass, enabling the construction of large and numerous buildings and city structures in a short time. Technological innovations, especially the elevator, allowed a decoupling from structural constraints, and the concept of space more closely followed function, leading to vertical growth (Corbusier, 1922). Cities changed their skylines dramatically. The city function was changing and enlarging, which created new social classes. Medieval cities had focused on protection and featured strong external walls, whereas modern cities are open and connected. Districts and neighborhoods underwent transition; although slums and wealthy areas were still separate, working-class districts emerged. As there was no public transport, the industrial workers lived close to industries, giving rise to workers' cities. With the growth of wealth, employers built houses for workers (a worker who sleeps better, works better).

Buildings were responsible for 32% of global final energy consumption in 2010, which was approximately 117 exajoules and 51% of global electricity consumption (Lucon et al., 2014). Energy is used in buildings mainly for heating, cooling, hot water, lighting, and appliances. Approximately 80% of this energy came from fossil fuel resources in 2015 (World Bank, 2019). To achieve a net-zero-energy or plus-energy building, it will be necessary to combine energy efficiency measures and the adoption of renewable energy technologies.

The Digital Revolution leads to further new materials and technological solutions that have the potential to improve internal conditions and to reduce the negative impacts of buildings on the environment. Smart homes make use of digital tools, technology, and information (IEA, 2017). Equipment and building parts have advanced features of their own, as well as interconnectivity to improve their operation. Smart homes have a system of sensors to monitor variables like temperature and occupancy, and they enable settings to be adjusted accordingly. The system can work with or without a connection with the outside world, and it can function with or without human intervention.

The global number of connected homes has been growing and is projected to increase steadily. According to Strategy Analytics, a big data analyst think tank, the penetration of smart homes is expected to grow worldwide from 4% in 2013 to 12% in 2019, and in the USA from 13% in 2013 to 38% in 2019 (Ablondi, 2014). According to their data, there were already 172 million smart homes in 2016 globally, which is expected to grow to over 300 million in 2020 (Strategy Analytics, 2019). Behind this trend, the penetration of connected smart home appliances is projected to multiply six times between 2017 and 2030, from around one billion to over six billion (Figure 38).

Integration of "smartness" into homes is best done at the construction stage; however, new construction is below 1% of existing stocks per year in Europe. A focus on deep renovation could provide a tipping point, and it might reduce the need for new constructions. The issue with costs is even more prominent in the Global South, where most new buildings will be built, and where decent housing is an issue in itself, with all the related environmental impacts. Additionally, there is a major disconnect in the longevity of smart devices and technologies (in the order of three to five years) and that of the buildings themselves (50–100 years), which may require continual retrofitting of new technologies and devices as they become obsolete. Harnessing the benefits of connectivity requires more than technology.

Today's buildings can adapt to their external conditions, utilize natural daylight, and adjust ventilation to regulate the internal conditions and optimize overall energy demand. Building energy management systems (BEMS) can enormously increase the efficiency of energy use in buildings. Recently BEMS has been combined with Building Information Modelling (BIM) systems, which control all systematic life cycle information of buildings. BEMS can optimize the effective energy use within whole combinations

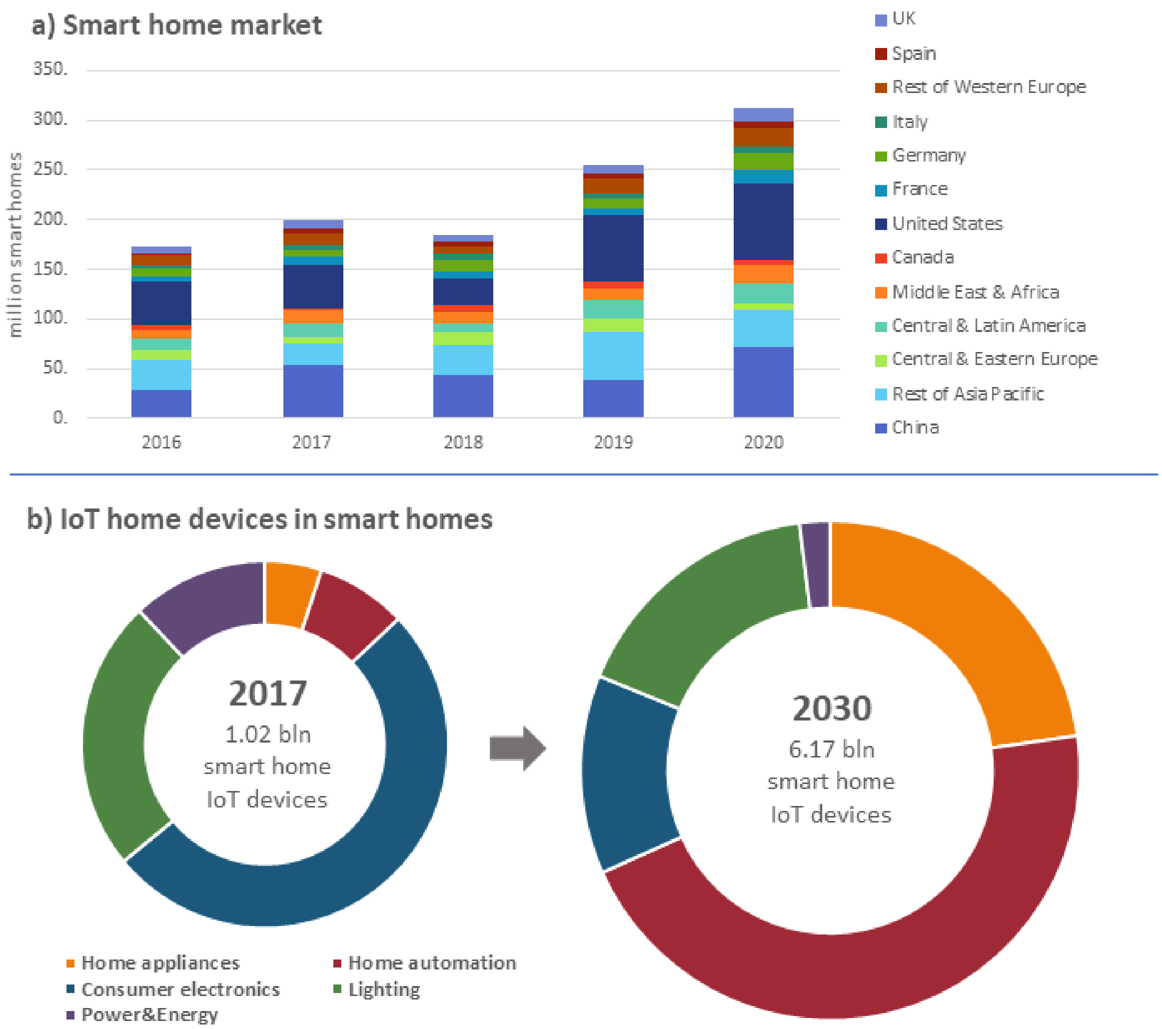

Figure 38. Home connectivity in recent years, in the near future, and in 2030. Panel (a) shows the growth of the number of smart homes, and the distribution among world regions and major economies; panel (b) presents the expected growth in smart home appliances. Source: Data from Strategy Analytics (2019).

of systems (e.g., onsite renewable production, natural ventilation, personal energy consumption patterns, and building mixed-use).

Progressive sustainable construction incorporates various sustainability aspects. These buildings integrate thermal sustainability and all other services of a building, using closed material reuse or recycling systems for water, wastewater, food waste, and construction materials (Ertsey & Medgyasszay, 2017). They may even be self-sufficient, such as the Net-Zero Projects by EPA (2018). Digitalization ensures that energy is consumed when and where it is needed, and it enables peak demand management, while predicting, measuring, monitoring, and reacting to what is happening within or around the house (IEA, 2017).

In addition to offering more comfort, smart homes increase health protection and security, and they are the source of huge amounts of data. Understanding personal energy consumption patterns within buildings can support projections in energy demand, which can be balanced with renewable energy generation. Building information may be linked with large public data sources in a timely manner to balance regional energy demands with onsite renewable energy production. By integrating smart buildings and renewable energy production, the smart grid concept is expected to create a fundamental efficiency and reliability improvements for the whole built environment. Automated control systems can optimize energy demand and network availability, delivering energy more effectively and enabling consumers to actively participate in the electricity market (Kolokotsa, 2016). Smart metering technology can support the delivery of intelligent services for households and building users. These data, as well as other energy and climate data, are used to analyze the complex relationship between energy consumption and variables such as temperature, solar radiation, and occupant behavior (Jain et al., 2014). However, to achieve this implementation, community governance and partnership are critical to ensuring that large-scale network systems are built and that the maximum potential of integrated sustainable actions in a community are realized (e.g., Figure 39). However, the issues of privacy and illicit access to personal date constitute a major challenge to the diffusion of smart and interconnected buildings.

Increasingly, homes are becoming much more than places for sleeping. Advances in computational design technologies have promoted the concept of flexible spaces over conventional spaces (e.g., offices, single-use buildings). The Digital Revolution may accelerate more "anonymous" shared spaces, which simply provide basic facility infrastructure that can be adapted for a number of different users (including anonymous users) depending on the situation. This may fundamentally change the value of land and property. Such multi-use shared spaces can dramatically reduce use of resources, energy, and materials; it can also lower transport costs and overcome location-specific constraints.

Such high levels of connectivity within homes do not come without significant risks, such as the potential for cascading or systemic failures, or loss of systems control. Critically, increasing connectedness increases the potential for malicious hacking. Beyond connectivity, digitalization also impacts the construction of buildings. Figure 40 shows a residential building that was "printed".

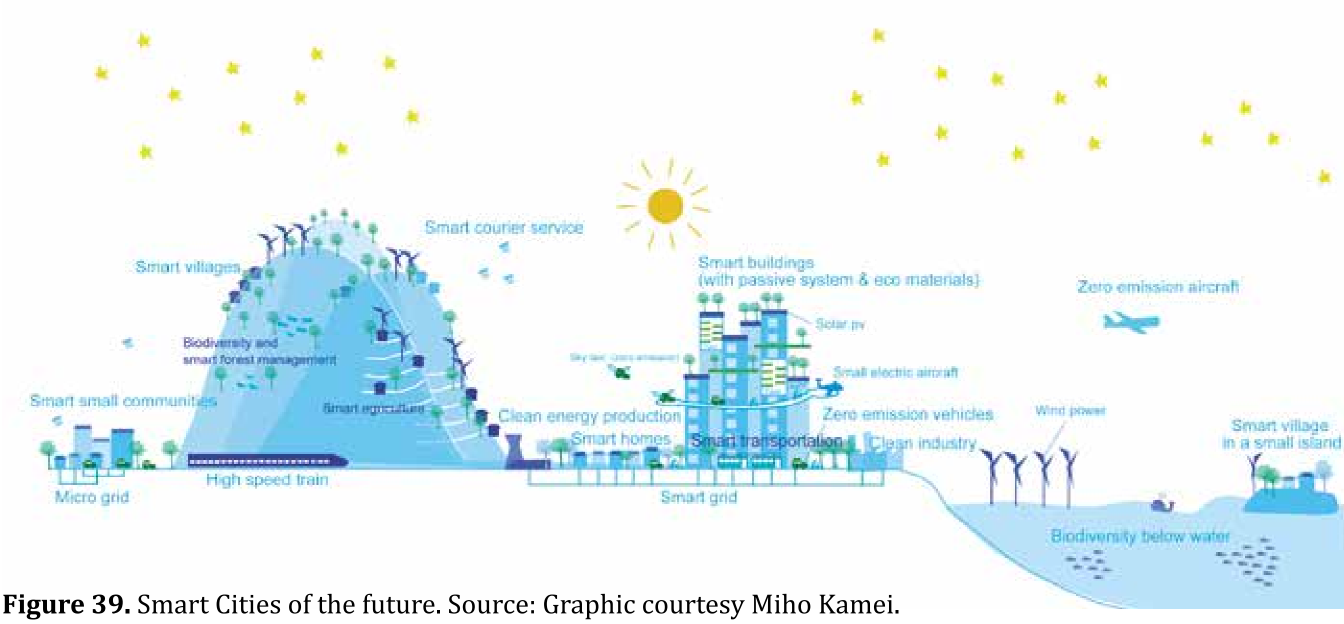

Figure 39. Smart Cities of the future. Source: Graphic courtesy Miho Kamei.

Figure 40. The first residential building in Europe printed with a 3D construction printer. Yaroslavl (Russia). Source: AMT-SPETSAVIA Group (Russia) – www.specavia.pro, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=74334750.

6 Governing the Transformation toward Sustainability in the Digital Age

The Digital Revolution has already begun the process of transforming humans into *Homo digitalis*, and it is a major determining factor in how we will live and interact. Clearly there are many societal challenges associated with increasing digitalization. If not managed carefully and thoughtfully, these challenges could lead to a significant counter-revolution – that is, a direction of development opposite that required to achieve the 17 SDGs. The hugely popular Netflix series *Black Mirror*, which depicts a technology-driven dystopia, is not necessarily that unbelievable given the seemingly unregulated current evolution of digital technologies.

However, it is equally clear that advances in technology offer huge societal benefits, if explicitly directed toward a sustainable future for all. The potential for major progress in education, health, equity, and prosperity, as well as the reduction of environmental degradation and of the damage to essential Earth-system functions, is undeniable (as explored with many examples in chapter 6). In addition, there will be societal impacts brought about by significant changes of to our lifestyles, work, leisure, and interaction with other members of our immediate, local, and broader communities.

Societies and their governments are standing at a critical crossroads that mark the type of future we want. Of course, it is possible that the current trends cannot be managed or regulated at all, given that the vigorous pace of innovation is creating new tools and techniques well ahead of the creation of guiding norms and policy – – and, indeed, well ahead of public awareness about the implications of the innovations. In the absence of a thoroughly examined, deliberate path for the introduction of new technologies, the consequences to the public good, global commons, and other natural resources are often confronted after the fact. By that time, the damage is already so large that it cannot be ignored, which leaves the public feeling deceived. However, the Digital Revolution could help provide the tools to inform the public about the positive attributes of new technologies and to engage their support up front as the technology improves and spreads. While public support is essential for the realization of the full potential of new technologies, public concerns will constrain the realization of their full commercial and financial deployment.

A compelling example of the importance of public perceptions and opinions in the context of the SDGs is the current relative lack of action on reducing carbon dioxide emissions toward zero. This is a herculean task that will require halving emissions every decade from now on (Rockström et al., 2018; IPCC, 2018). The biggest obstacle to the introduction of a carbon tax is public perception and acceptance. A diligent and open discussion with the public could be the decisive step that provides a solution to the problem, clarifying the public's favored options (Carattini et al., 2019). However, there are new contemporary social movements that are rapidly building a global force in favor of strong political action to tackle climate change issues, as evidenced by the recent school strikes (often associated with the 16-year-old Swedish campaigner, Greta Thunberg), and these have expanded to all continents and attracted a million activist followers.

The simplest of the new technologies that will cause disruptions in the very near future may be autonomous vehicles (AV), which are a mere step away. Their introduction should take note that "if commonsense protections are not in place to govern AV development, and problems occur, the public will reject autonomous vehicles, and the opportunity this new technology presents to improve public safety will be lost" (Claybrook & Kildare, 2018). This is a simple but very powerful argument, which should be applied and extended to innovation and technology in general.

The creation of ever more powerful technologies with ever less intuitive consequences may, if left unchecked, aggregate in problems that the public will vehemently regard as unacceptable. A public that feels cheated and used through the adoption of technologies will respond like postmodern critics of science: in terms of power, the status quo, relativism, and alternative truths. The Digital Revolution could provide new means of public engagement and participation in new technologies.

Governing the digital transformation is a challenge because the "ship has to be built while being on sea." We do not have a clear picture what a digitalized world will look like. Simple and small governance innovations might help, but they will not be enough. We identify a set of guiding principles for governing the transformation toward sustainability in the Digital Age:

Creating the missing links between digitalization and wealth creation: The mobilization of the enormous potential for a digital sustainability transformation is not a matter of course. Digitalization has worked in recent decades more as an accelerator of economic processes that are still predominantly based on fossil energy and resource extraction. The production and operation of short-lived electronic devices alone is a key driver of energy and resource use. For example, a smartphone contains almost all chemical elements, so recycling is important but resource intensive. A trend reversal is required. Without politically designed course corrections toward sustainability, the dynamic of unrestrained digitalization threatens to drive the world further into a hyper-consumer society, thus jeopardizing the success of the sustainability transformation. Digital upheavals can also compound many social problems, such as inequalities or the erosion of state control.

However, if course corrections succeed, then the disruptive impact of digitalization can be leveraged to accelerate and enhance the sustainability transformation. Digitalization can then advance the decarbonization of energy and mobility systems, the comprehensive circular economy, resource and energy efficiency and sufficiency, sustainable urban transformation, and ecosystem monitoring and protection. There is a need for corresponding and commensurate policies, which at present exist only in a small number of sectors and a limited number of countries. Six key mechanisms can help create the "missing links" between digitalization and sustainability.

First, by systematically integrating sustainability requirements into their research and innovation processes, pioneers in digitalization research could help to develop mission statements of digital sustainability.

Second, fair pricing of greenhouse gas emissions and green levies and tariffs need to be geared to the consumption of natural resources rather than to labor. Currently, it is the latter that is the foremost source of taxation. Tax reform could be a powerful way of driving digital innovation toward sustainability.

Third, markets could be shaped by clear government sustainability goals, as well as sectorial and regional transition roadmaps. This could incentivize and mobilize digital technologies and their disruptive potential to implement sustainability transformations with appropriate time urgency.

Fourth, significant state modernization programs need to be launched to rapidly increase the digital skills of public institutions and their ability to connect with sustainability transformations. Without digital skills, a responsible approach to the digital changes is impossible. Artificial intelligence could be integrated as a new actor as part of a governance system.

Fifth, sustainability and digitalization researchers have hitherto operated in separate silos. It is imperative to improve collaboration and integration, so that there is a holistic perspective from which to gain knowledge about transformation pathways toward digital, sustainable societies.

Sixth, we need to support dialogue networks that connect business, government, civil society, and science. These networks will enable the goals, limits, and normative framework conditions of a digital, sustainability society to be negotiated. This will require policymakers, researchers, companies, and civil society actors to multiply their efforts to understand and explain the effects of digital change. These networks will span national and established transnational borders, because digitalization and data do not stop at any borders.

These six mechanisms are fundamental, necessary conditions for enabling and accelerating the sustainability dynamics in the Six Transformations (Figure 41).

To accelerate processes of change as initiated by the implementation of the six mechanisms, we suggest creating spaces for local experiments. These labs of innovations would demonstrate how digital dynamics can foster sustainability transformations: cities implementing shared mobility systems in order to reduce the number of cars could be supported; regions starting to build fully circular production and consumption chains could get access to favorable finance; universities, aiming at systematically integrating research on sustainability, artificial intelligence, automated decision-making systems, and virtual spaces, should be promoted. Investing in the power of creativity, innovation, and experiments could help pave the way to sustainable digital societies.

Developing normative and institutional innovations and guardrails for sustainable digital societies: Governing digital disruptions is not only about some good policies to link economic development pathways with digital innovations. In the 21st century, digitalization will change the basic structures of our societies as fundamentally as the Industrial Revolution led to deep transformations in the 19th century. A new society is emerging, and even a new era of humanity: the Digital Anthropocene. We demonstrated that digitalization could multiply "slippery slopes," which are already threatening many societies: economic and political power concentration; multiple inequalities; privacy and citizen rights under stress; and governance capacities of nation states eroding. The impacts of digitalization on labor markets could be huge.

Figure 41. TWI2050 focuses on Six Transformations that capture much of the global, regional, and local dynamics and encompass major drivers of future changes: (i) Human Capacity & Demography; (ii) Consumption & Production; (iii) Decarbonization & Energy; (iv) Food, Biosphere & Water; (v) Smart Cities; and (vi) the Digital Revolution. Together, they provide a people-centered perspective, enabling the building of local, national, and global societies and economies that secure the wealth creation, poverty reduction, fair distribution, and inclusiveness necessary for human prosperity. They are necessary and potentially sufficient to achieve the SDGs if addressed holistically and in unison. Source: TWI2050 (2018).

Against this background, it will be critical to balance digitalization and social cohesion. But the drivers of change will produce even more fundamental shifts: automated decision making or supporting systems will, based on big data analysis, penetrate courts, health systems, parliaments, private businesses, military organizations, police, and universities. How will we balance deliberation between humans, as a basic pillar of all our societies and the international system, with artificial intelligence and deep-learning-driven decision-making systems? What does all this mean for the future of democracy? Where digital monitoring and tracing technologies meet authoritarian regimes, democracy and freedom are at stake. Human transformation, human enhancement, and ever deeper interactions between humans and technical systems will rapidly develop further. Human integrity and dignity need to be reinvented against the background of these fundamental developments.

At the same time, there are many opportunities, as discussed in this report: revolutionary health innovations will emerge; people around the globe can now interact, learn, and cooperate in virtual spaces; and there is likely to be a huge explosion of knowledge. In this era of transformative change and disruption, we should learn from Adam Smith and Karl Polanyi. Smith, who was both an economist and a moral philosopher, argued in his *Wealth of Nations* (1776) that markets, technological revolutions, and deep changes within societies could only work without destabilizing societal systems if the autonomy of markets is constrained by society's norms and values. Unless digital change is embedded in strong systems of values and norms, the dystopian potential of digitalization will prevail. Therefore, normative guardrails for the Digital Age need to be developed (WBGU, 2019). The analysis of trends of digitalization demonstrates that their impacts move into new societal territories, and this is something that is still not covered by the 2030 Agenda. TWI2050 therefore suggests the initiation of local, national, and global dialogues on appropriate norms and values for the Digital Anthropocene.

Learning from Adam Smith's knowledge on the normative foundations of societies is important, but it is not enough. Karl Polanyi, as well as Max Weber and other thinkers, agreed with Adam Smith, but they took a vital further step. Norms can only be successfully anchored in societies and protected from powerful interest groups if institutions are created that can deal with the changes and steer individual and collective action into corridors agreed on by society. Institutional innovations and guardrails are needed to develop pathways toward a sustainable digital future. Our message is: digitalization is not only a process of accelerating technological change, but a civilizational shift requiring deep normative and institutional innovations and guardrails.

Investing in future-oriented science and education: In times of deep changes and uncertainties, science could help to generate future-oriented knowledge about possible pathways toward sustainable digital societies. Science policy could support four major contributions of science to a sustainable digitalization. First, just as climate and Earth-system research was brought together with social sciences and economics four decades ago to form sustainability sciences, the challenge now is to build bridges between the sustainability sciences and digitalization-oriented research (Figure 42). To shape artificial intelligence, virtual realities, automated decision making, and supporting systems toward sustainability, and to understand deep digital transformations and their societal impacts, new research communities have to be developed.

Second, we need to change the narrative about "governing the digital transformation" by enabling innovative research that departs from the analysis of challenges and threats of technological developments, and instead focuses on new ideas and solutions – that is, we need to create a positive narrative of synergies of suitability for all (Box 13).

Third, research communities should interact systematically with the private sector, civil society, and political decision makers at all levels. Transdisciplinary research and dialogues would help to develop joint perspectives, democratically accepted heuristics, and mental maps of what sustainable digital societies could

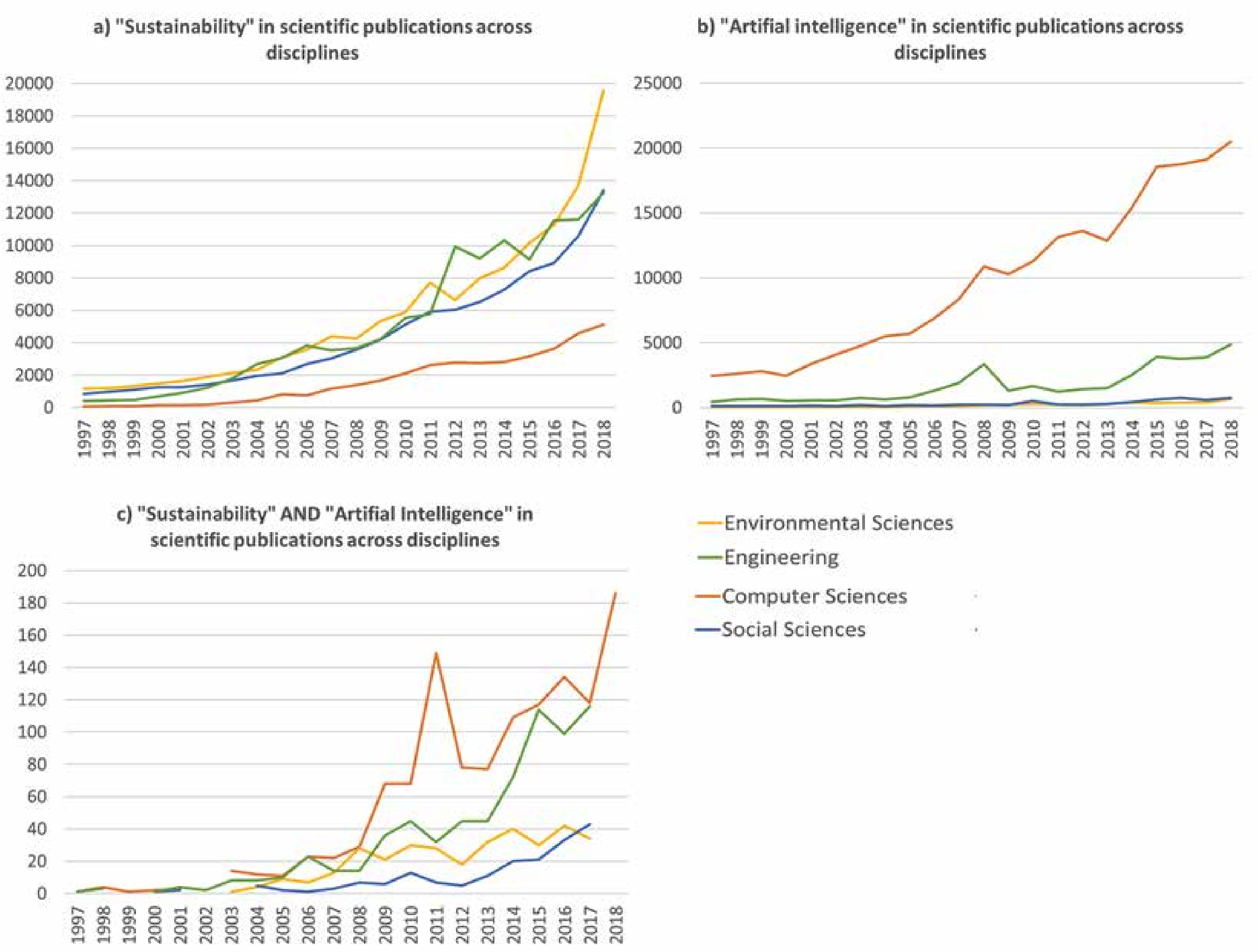

Figure 42. More integrative science is needed to cover advances in digital technologies (e.g., artificial intelligence) and the interconnections of digital technologies with sustainability. Computer sciences are lagging when it comes to their role in sustainability (panel a), while artificial intelligence is not yet a topic of interest to disciplines outside computer science (panel b). Combining the search terms "sustainability" and "artificial intelligence" reveals that computer science and engineering are ahead of the social and environmental sciences in their research output level by a factor of 100 (panel c). Source: Data from SCOPUS.

Box 13. Data Trusts: An Agreement between Citizens, Governments and Firms for Data Use

Private firms are not, by nature, providers of collective goods in the way that governments are, which is a problem if the focus is on bringing digital technology solutions to the massive governance challenges that must be addressed in the 2030 Agenda. This does not mean that digital technologies cannot play a role in helping solve these problems; it does mean that managing the politics of technology and data will play a key role in the effective digitalization of the 2030 Agenda. Regulating the use of data is an important starting point, since user data is central to the participation of Internet firms in governance processes. In the years since the 2016 US election, there has been increased scrutiny and public debate about how social media and Internet platforms manage user data. The revelations about Facebook selling user data to firms like Cambridge Analytica, and the ways that state actors can use psychometric data to target batches of users with tailored posts, pose significant challenges to good, inclusive governance and political participation.

One promising approach to reestablishing trust between users, software firms, and governments is the establishment of data trusts. Although the concept is still being debated, there are some generally agreed features of what constitutes a data trust. In the context of data used in smart city applications, data trusts can take the form of a fiduciary trust between citizens, government, and data firms (Wylie & McDonald, 2018). These kinds of fiduciary agreements give all parties input into how data are used in different jurisdictions. The agreements are flexible, and they prevent data capture by private actors who answer to shareholders. This can create an ethical, transparent mechanism for storing and using sensitive data, like medical information, for activities, such as developing artificial intelligence and machine learning tools for public health, which is currently being explored by the National Health Service in the UK (Mehonic, 2018). As noted, data trusts are still a concept that is being developed, and different governance entities have different definitions and approaches to understanding them. The OECD takes a local-level view on what constitutes a data trust, embedding the process that determines data-sharing rules at the community level, with the communities then determining among themselves the data-sharing rules across jurisdictions (Hardinges, 2018). Although not all data requires something like a trust or fiduciary arrangement, trusts can go a long way toward establishing transparency and trust between citizens, governments, and firms about what constitutes appropriate, ethical use of data for.

and should look like. Currently, digital innovations are mainly driven by private R&D investments. To develop societal perspectives on sustainable futures, public R&D investments are instrumental.

Fourth, fundamental and basic research should be complemented by research investments in real-world experiments (future labs) that aim to build rapidly sustainable digital mobility, as well as urban, energy, and educational systems.

Fifth, research and knowledge hubs on sustainable digitalization should be created and significantly strengthened in the Global South to ensure that developing countries can also become drivers of transformations toward sustainable digital societies. Beyond science, comprehensive education on sustainability is a precondition for enabling the next generations to understand and shape the dynamics of fundamental change.

Creating attractive narratives and visions to shape the future: a New Humanism (WBGU, 2019) for the 21st century: The Renaissance, which built bridges between the Middle Ages and the Ages of Enlightenment and the Industrial Age, was characterized by three major revolutions or transformations: (i) the emergence of a new world view (Copernicus); (ii) the breakthrough and impacts of a communication revolution (the printing press); and (iii) a cultural and religious transformation (the Reformation). These three shifts revolutionized European societies. Something similar is happening now at the beginning of the Digital Age. First, the Digital Age is producing a new virtual, global, just-in-time communication revolution. Second, the Digital Anthropocene will trigger new world views, redefining our perceptions of humans, of intelligence, of boundaries between humans and technical systems, of science, and of the planet. Third, we will also probably see profound cultural transformations. We suggest, therefore, that we should start developing a "New Humanism" (WBGU, 2019) for the Digital Anthropocene as a tool that might help to avoid the dystopian potentials of digitalization.

Some elements, ingredients, and starting points of a New Humanism have been discussed in this report: knowledge expansion will open new doors to economic, social, and cultural innovations; digital technologies will enable transnational communication and learning; virtual spaces will support the creation of transnational networks and communities. All this could foster a culture of global cooperation, of global world views, and of humans as a *community of destiny*. Furthermore, given the digital technologies that enable us to monitor, analyze, and understand the Earth system as never before, it could also lead to a *global environmental consciousness.*

The New Humanism should defend the basic values of the Enlightenment (i.e., human dignity, human rights, freedom, equity, rule of law, democracy) and embark on a renewed understanding of humanism in the Digital Anthropocene, taking on board perspectives that have been neglected or not taken seriously during the last three centuries. The following questions might indicate some significant dimensions of a renewed concept of humanism in the 21st century. How could we mobilize the potentials of human emotions, empathy, care, and solidarity to go beyond our cognitive capacities? Can artificial intelligence help us to understand and better use our social intelligence as a key competitive advantage and a major cornerstone of societal progress? Can we complement our understanding of individual freedom with a stronger emphasis on humans as social beings who are embedded in communities and societies? Can we develop further our thinking on the importance of social cohesion and equity for human wellbeing? Can digital innovations help us to readjust the relationship between humanity and the planet? Can we develop a global culture of responsibility for Earth-system stability and a healthy planet? Can a global commons perspective – on climate issues, the oceans, global land use, as well as on financial markets and international security networks – gain in importance? Can humans learn to be embedded in their local and national communities while at the same time identifying themselves as global citizens? Can all of this be leveraged by the global communication revolution and the unprecedentedly dense transnational networks of people? How can we govern beyond borders more effectively and establish a transnational governance system? And last, but not least: How are we going to define the future of humans, now that we are becoming equipped with technologies that allow for different types of human enhancement or even artificial evolution?

These reflections about a New Humanism open the door to renewed thinking about sustainability in the Digital Anthropocene. Keeping in mind the image of us having to build the ship while at sea, we end the report with these open questions and invite researchers, political decision makers, private businesses, and civil society to gather and invest in finding answers to these questions so as to ensure that we find a pathway toward a sustainable future for all.

Abbreviations

AI	Artificial intelligence
AIS	Automated identification systems
AM	Additive manufacturing
AR	Augmented reality
AV	Autonomous vehicles
BEMS	Building energy management system
BIM	Building Information Modelling
CAD	Computer-aided-design
CGI	Computer-generated imagery
DRE	Decentralized renewable energy
DSO	Distributed system operator
EPA	Environmental Protection Agency
ETF	Equity trading fund
FOSS	Free and open source software
GAP	Grid access planning
GHG	Greenhouse gas
IAM	Integrated assessment modeling
ICT	Information and communication technologies
IUU	Illegal, unreported, unregulated
IoT	Internet of Things
LDC	Least developed countries
LiDAR	Light detection and ranging
MMORG	Massive multiplayer online role-playing game
MOOC	Massive open online courses
NMR	Nuclear-magnetic resonance
PCA	Principal components analysis
REM	Reference electrification model
SaaS	Software-as-a-service
SDG	Sustainable development goals
SDP	Sustainable Development Pathway
SHS	Solar-home systems
STI	Science, technology, and innovation
TWI2050	The World in 2050 Initiative
VIO	Vehicles in operation
VR	Virtual reality
XR	Extended reality

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1. A new era in human history is emerging! After Neolithic and Industrial, the Digital Revolution is the next era!
2. Digital technologies can enable a disruptive revolution toward a Sustainable Anthropocene!
3. Governance is urgently needed! The disruptive dynamics of digitalization are challenging the absorptive capacities of our societies and threaten to erode social cohesion.
4. The Digital Revolution opens the door to a quantum leap for human civilization!
5. We need to resolve the paradox of the Digital Anthropocene: Digitalization is creating the essential preconditions for TWI2050 Six Fundamental Transformations toward sustainability, yet it is also endangering them!
6. Human enhancement and augmentation present an uncertain future for our species! *Homo sapiens* is being transformed into *Homo digitalis*.
7. We need to understand and overcome the "retarding moments" of innovation breakthrough!
8. We need to build responsible knowledge societies capable of moving toward sustainability in the Digital Age!
9. The clock is ticking toward 2030 – we have only 10 years to meet our Sustainable Development Goals!