Innovations for Sustainability

Pathways to an efficient and sufficient post-pandemic future

3rd Report prepared by
The World in 2050 initiative

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COVID-19 RESPONSE

TWI2050 The World in 2050

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Foreword

Innovation has been the foundation of human and societal development since the dawn of civilization. It has resulted in enormous benefits for human wellbeing while at the same time is has brought the world to a critical crossroads where further unconstrained development risks societal and environmental collapse. The current rate and direction of innovation is insufficient to achieve the United Nation's (UN) ambitious goals for an inclusive sustainable future for all, in part because of a relatively narrow focus on technology innovation without also addressing societal, institutional, and cultural innovation. We need to rebalance so that all dimensions of innovation and invention are promoted simultaneously, including addressing inequities. We also need to develop more proactive efforts to promote diffusion and learning, and to address barriers, constraints, and unintended consequences of innovations.

We live in interesting times. They are times of great dangers and uncertainty for humanity and the planet, but times of unprecedented opportunities for directing development toward a just, resilient, and sustainable future. The current coronavirus disease 2019 (COVID-19) pandemic is disrupting the status quo, providing an opportunity to create sustainable societies with higher levels of wellbeing for all and mitigating environmental impacts at all scales. Properly directed, the stimulus packages underway to restart economies can ignite and leverage effects toward sustainability. The risk is that they may promote resurrection of the 'old normal,' going back to business-as-usual, rather than a transformation toward sustainability.

This report, which focuses on innovation, is the third by The World in 2050 (TWI2050) initiative that was established by the International Institute for Applied Systems Analysis (IIASA) and other partners to provide scientific foundations for the UN's 2030 Agenda for Sustainable Development. This report is based on the voluntary and collaborative effort of more than 60 authors and contributors from about 20 institutions globally, who met virtually 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 conferences 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 and health; ii) Consumption and production; iii) Decarbonization and energy, iv) Food, biosphere and water; v) Smart cities; and vi) Digital Revolution.

The focus of the second report, *The Digital Revolution and Sustainable Development: Opportunities and Challenges,* launched in 2019, was the Sixth Transformation. Although it could arguably become the single greatest enabler of sustainable development, it has, in the past, helped create many negative externalities like transgression of planetary boundaries. 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 of future solutions; at the same time it potentially carries strong societal disruptive power if not handled with caution, care, and innovativeness.

This third report, *Innovations for Sustainability: Pathways to an efficient and sufficient post-pandemic future,* assesses all the positive potential benefits innovation brings to sustainable development for all, while also highlighting the potential negative impacts and challenges going forward. The report outlines strategies to harness innovation for sustainability by focusing on efficiency and sufficiency in providing services to people, with a particular focus on consumption and production. It concludes with the related governance challenges and policy implications.

Completion of this report has involved voluntary 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 who have provided substantial in-kind support and the vision needed to conduct an initiative of this magnitude. Special thanks go to the Chapter lead authors Geoff Clarke, Kris Ebi, Arnulf Grubler, Julia Leininger, and Sander van der Leeuw, and all authors and contributors without whose knowledge and dedication this report would not have been possible and who contributed despite the challenging circumstances.

The publication of this report in July 2020 and its launch during the United Nations High-level Political Forum is timely. TWI2050 outlines ten key messages on the linkages between innovation, efficiency and sufficiency, and the sustainability transformations. Despite the magnitude of the challenge and the current unsustainable direction of development, additionally impacted by the COVID-19 pandemic, the transformation to a sustainable future is achievable—we have the knowledge, means, and capacity. However, at this point in time, with only 10 years until 2030, there is a general lack of political will within many governments across the globe to mobilize the necessary resources and make the required policy and structural changes to achieve the 2030 goals. It is our belief that this report will provide policy and decision makers around the world with invaluable new knowledge to inform action and commitment toward achieving the SDGs in these interesting and challenging times. The level of global commitment and cooperation displayed during the development of the 2030 Sustainable Development Agenda needs to continue and deepen during this critical implementation phase. We hope this report provides a roadmap toward a sustainable future in a 'new' post-COVID-19 world and will divert from the 'old' alternatives that both transcend the planetary boundaries and leave billions behind.

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Key Messages

1. **The world is at a crossroads.** Only 10 years to go to achieving the 2030 Agenda and progress to date has been slow. The world is not on track to achieve the majority of the aspirational and ambitious SDG targets. Achievement of the 2030 Agenda is possible, but choices need to be made and require political will toward "accelerated action and transformative pathways: realizing the decade of action and delivery for sustainable development."
2. **Ensuring a just and resilient sustainable future for all** will require socioeconomic development for improved human wellbeing while preserving Earth-system resilience. There is increasing inequality within and between societies with billions left behind and overwhelming evidence of rising global risks due to ever-increasing human pressures on the planet.
3. **The COVID-19 pandemic is a great and immediate threat to humanity,** especially for those with previous health risks and those deprived through poverty, lack of health care, and living in fragile states. It is challenging the status quo, providing an opportunity for disruptive and accelerated change. Properly directed, the stimulus packages underway to restart economies can ignite and leverage effects toward sustainability. Creating employment opportunities out of the crisis is a high priority, but the risk is that they may promote resurrection of the 'old normal.'
4. **Six TWI2050 Transformations provide the necessary framework** for how to achieve a sustainable, just, and resilient future. Jointly these transformations can accelerate actions within the next decade. As they take place in systems whose evolution depends on governance, values, policy tools, etc., they can be managed and socially steered as their outcomes depend on choices and human intentionality. Moreover, because the Six TWI2050 Transformations interact with all the SDGs, they provide an entry point for achieving them.
5. **Transformative governance is emerging but unfavorable political contexts threaten innovation**. There is a growing understanding of how governance needs to be designed for integrated SDG implementation. However, if global political trends—autocratization, fracturing of societies, lack of global cooperation, and distrust of science—continue to unfold, the sustainability transformation will be difficult to achieve.
6. **Science, technology, and innovation are at the core of human progress** and have contributed to explosive development, such as the doubling of life expectancy, providing secondary education for half of humanity, and the wellbeing of billions, but paradoxically they have also brought about negative environmental and societal impacts. At the same time, Science, Technology, and Innovation (STI) are a collective learning process that can provide many possible solutions for achieving a sustainable future for the people and the planet.
7. **Granular innovations can be expected to have faster adoption and diffusion,** lower investment risk, faster learning, more opportunities to escape lock-in, more equitable access, higher job creation, and larger social returns on innovation investment. In combination, these advantages enable rapid change. For such rapid transformation to occur investments should be directed toward innovations with high learning and diffusion potentials. This is also critically important for the achievement of the Six TWI2050 Transformations—from digitalization to decarbonization and health.
8. **Prioritize the renewal of the science-policy-society interface for evidence-based transformations.** While states with higher investments in research and development and enlightened leadership perform better in managing the COVID-19 pandemic, we need a renewed global science-policy-society interface built on a culture of trust, communication of accurate information, and a reinvigoration of global science organizations.
9. **Transforming service-provisioning systems is about safeguarding human needs and sharing available resources** fairly within planetary boundaries. The central question is which types of technological and social innovations can contribute to decreasing inequalities, increasing resilience and our collective ability to deal with crises, while also decreasing the pressures on natural resources. To achieve accelerated change, the world needs to move away from a supply-driven model of development to one that is low-demand and services-driven and that is based on efficiency and sufficiency, while focused on providing wellbeing and decent living standards for all.
10. **Transnational crises require global context-sensitive responses**. Investing financial resources and nonmonetary support to assist local and municipal actors and international organizations is key. The COVID-19 pandemic demonstrated system-wide weaknesses in implementing an early and effective global response. However, if the right lessons are learned, it provides significant opportunities to accelerate the societal consensus and political reforms needed to achieve the sustainability transformation.

Add as many mail-coaches as you please,
you will never get a railroad by so doing.
Joseph Schumpeter (1883–1950)

1 Creating a sustainable Anthropocene

1.1. Nature of the challenge

The predicament of humankind is how to realize the benefits of global social and economic development within a safe and just operating space of a stable and resilient Earth system. There is increasing inequality within and between societies with billions left behind and overwhelming evidence of rising global risks due to ever-increasing human pressures on the planet. Ensuring future resilient sustainable development for all will require socioeconomic development for improved human wellbeing while preserving Earth-system resilience (Rockström et al. 2009, Steffen et al. 2015, TWI2050 2018).

In 2015, the United Nations (UN) adopted the 2030 Agenda for Sustainable Development (UN 2015b) that provides an aspirational narrative and an actionable agenda to be achieved by 2030, including 17 Sustainable Development Goals (SDGs) and 169 targets for the desired future for human development. It specifies far-reaching time-bound, often quantified, objectives based on the most comprehensive consultation among nations and civil society. For the first time, a world development agenda was adopted that integrated comprehensive and ambitious goals for inclusive social and economic development for all, to occur in parallel with achieving global environmental targets for land, oceans, freshwater, biodiversity, and climate; thus protecting the global commons (Nakicenovic et al. 2016): This essentially means a roadmap for redefining sustainable development as a people and planet agenda for achieving a prosperous and fair world within planetary boundaries. The 2015 Paris Agreement (UNFCCC 2015) that commits all signatories to a long-term target of holding global warming to "well below 2°C" and if possible below 1.5°C above preindustrial levels, as well as the 2015 Addis Ababa Action Agenda (UN 2015a), increased the urgency for achieving the 2030 Agenda. Central to the overarching goals is the recognition of the necessity of attaining inclusive and fair social and economic development within the safe operating space of a stable and resilient Earth system.

However, the world is not on track to achieve the majority of the aspirational and ambitious SDG targets within the next decade. As such, the focus of the UN's High-level Political Forum (HLPF) on Sustainable Development for 2020 is for "accelerated action and transformative pathways: realizing the decade of action and delivery for sustainable development."[1] A prerequisite for achieving these aspirational and ambitious socioeconomic goals requires a fundamental transformation of the combined human and Earth systems (TWI2050 2018).

Humanity has entered a new geological Epoch, the Anthropocene, where humanity—one species—constitutes the largest driver of planetary change. Global environmental risks at all scales are high and rising. Several planetary boundaries that regulate the stability of the Earth system have been transgressed (Rockström et al. 2009, Steffen et al. 2015), and thereby the ability of Earth to provide essential support functions, fundamental conditions for good and healthy lives, and ultimately a stable state of the planet is in danger. However, there is a general lack of political will within many governments across the globe to mobilize the necessary resources and make the required policy and structural changes. It is critically important that the level of global commitment and cooperation displayed during the development of the 2030 Agenda continue unabated and be strengthened.

Humanity is at a crossroads: sustainable development is feasible at all scales—local to global—if stakeholders (national governments, cities, businesses, academia, and civil society) adopt actions in line with the SDGs under the 2030 Agenda and the Paris Agreement. Success is a matter of choice rather than inevitability or infeasibility. Choice requires the deployment of economic, political, and social instruments, technological and cultural innovations, and changes in lifestyles to bring about the needed transformational changes at every scale. It is a test of the capacity of the joint global community at all levels—in real time—to live up to what is necessary to do to enable a politically agreed and culturally accepted robust result to safeguard the necessary planetary conditions for the future. Despite the magnitude of the challenge and the unsustainable nature of the current trajectory, we have the knowledge, means, and capacity to move into a sustainable and resilient pathway. The needed transformations are beginning in some sectors and regions, however, much more is needed. Investing in high-quality education, well-functioning health systems, efficient and zero-carbon energy systems, environmental conservation and restoration, healthier

1 https://sustainabledevelopment.un.org/hlpf/2020

and adequate food systems, more sustainable lifestyles, good governance, and global cooperation initiatives would leverage implementation of the SDGs (Sachs 2020).

A new wave of nationalism, populism, ethnic awareness, and loss of values is emerging in many countries. Wide segments of the global population feel threatened by accelerating change, often driven by globalization processes, digitalization, robotic advancements, and other social and cultural phenomena. Even the suggested solutions connected to the sustainable development transformation itself (and its broad agenda) might be seen as threatening in many quarters, not dissimilar in style to the human reactions in earlier historical phases characterized by rapid change (e.g., during the Industrial Revolution). In 2019 this has been exacerbated by the coronavirus disease 2019 (COVID-19) pandemic, one of the greatest immediate threats to humanity. The closing of borders and increasing 'my country first' attitudes have further amplified the perceived threats, failures, and lack of resilience in global economic, social, and natural systems. Resilience refers to the capacity of a system to absorb major external disturbances and shocks (Holling 1973), and even though many have warned of a possible major pandemic, it poses an incredibly difficult challenge of having a resilient system to overcome the COVID-19 pandemic and the possible major crisis in its aftermath. Rather than restoring the status quo or business as usual, improvement of systems resilience should be seen in the context of transformative change toward a just and sustainable future for all despite backlashes, setbacks, and major disturbances on the way forward. In other words, we define resilience as the ability of a system, or rather humanity, to pursue the transformation toward sustainability while managing systemic risk of disasters and inherently unpredictable shocks over time in a mutually reinforcing way (Keating et al. 2017, Laurien and Mechler 2020).

The challenge is to what extent can systemic risks like COVID-19 have set back progress? Yet at the same time, the COVID-19 pandemic has brought out some of the best human characteristics; self-sacrifice in helping others; empathy and solidarity despite the need for social distancing. This has also provided an opportunity to build positive narratives oriented toward future, human-centered visions on local, national, and global levels. We need significant investments in social cohesion and robust transformative alliances to enable resilient sustainable development and to avoid societal backlashes driven by insecurity, injustice, and disenfranchisement. It is even more important now to integrate social and economic goals with climate, water, oceans, biodiversity, and other Earth systems so that sustainable development is not threatened in the long term.

1.2. Six grand transformations toward achieving the SDGs

Six Transformations (TWI2050 2018) capture the global, regional, and local dynamics needed to achieve the SDGs while reducing their complexity: (i) Human capacity, demography and health; (ii) Consumption and production; (iii) Decarbonization and energy; (iv) Food, biosphere, and water; (v) Smart cities; and (vi) Digital Revolution. These transformations include the major drivers of future change. All of these transformations are underway to some extent. Accelerating actions within the next decade implies further deep structural changes, 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. Transformative governance is required as well.

It is essential that local to international actors move beyond the sectoral and fragmented approach characterizing much sustainability research and implementation. Rather than only investigate the separate roles of water, or food, or energy, or even the water-food-energy nexus, true integration is needed across all possible domains affected, taking a holistic perspective that includes trade-offs and co-benefits. Science, Technology, and Innovation (STI) can be harnessed to accelerate progress. The holistic approach incorporates 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.

The Six TWI2050 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, but rather to describe systemic and integrative changes related to all SDGs, as illustrated in Figure 1. They are interlinked with all SDGs and interdependent, and together are central to 'turning the tide' of change to sustainability and resilience.

1.2.1. Why these Six Transformations?

The Six Transformations have a people-centered perspective: building local, national, and global societies and economies that secure wealth creation, poverty reduction, fair distribution, and inclusiveness necessary for human prosperity in any society everywhere. Each country will pursue the transformations differently. Universal domains of action include: (i) institutions to enable and improve human capacities and capabilities, populations that enjoy secondary and tertiary—not just primary—education, adequate access to health care, fair labor markets, universal rule of law, and means for

Figure 1. 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, and health; (ii) Consumption and production; (iii) Decarbonization and energy; (iv) Food, biosphere, and water; (v) Smart cities; and (vi) Digital Revolution. Together they give a peoples-centered perspective: building local, national, and global societies and economies which secure wealth creation, poverty reduction, fair distribution, and inclusiveness necessary for human prosperity. They are necessary and potentially sufficient to achieve prosperous, inclusive, and resilient sustainability transformation embedded in the SDGs if addressed holistically in unison. Source: updated from TWI2050 (2018).

managing aging societies; (ii) essential and strategic infrastructure for local, national, global economies and societies, such as energy, food systems, cities, settlements, and mobility systems; (iii) production and consumption systems that create wealth and ensure a good work-life balance, aiming at leaving no one behind; and (iv) STI that furthers progress toward achieving the SDGs (Box 1).

Further, all of the Six Transformations are associated with powerful dynamics that could result in very different development outcomes for humanity—positive and negative. At the same time, these transformations take place in systems whose evolution depends on governance, values, policy tools, etc.; that is, these can be managed, and the outcomes depend on choices made by humans. Moreover, because the Six Transformations interact with all the SDGs, they provide an entry point for achieving them.

It is worth noting at this stage that these Six Transformations differ slightly from those articulated by Sachs et al. (2019).[2] The salient elements remain consistent albeit with slight modifications. What is essential is that the Six Transformations reduce the complexity of the 17 SDGs and their 169 Targets into a more consistent framework that renders achievement of synergies easier, especially in terms of the needed policy levers. For the purposes of consistency with previous TWI2050 reports we have chosen to retain the original formulations of the Six Transformations for this report.

The Global Sustainability Development Report (GSDR 2019), like the TWI2050 (2018) report, highlights the importance of the 2030 Agenda and provides science-based conceptual frameworks for achieving the SDGs (Box 2). The need for transformational change is central to both reports and both argue for the reduction of complexity, conflicts, and trade-offs while maximizing synergies. Working toward the goal of complexity reduction, the GSDR describes six entry points to the needed transformations that are complementary to the TWI2050 Six Transformations. Both reports capture all 17 SDGs in an integrative and holistic manner and demonstrate the indivisibility of the 2030 Agenda.

As argued above, focusing on individual or selected SDGs—during policy analysis or implementation—comes with the danger of adverse side effects in other SDG domains or missing out on potential synergies and resulting multiple co-benefits. A holistic systems perspective helps to prevent lock-ins and

2 Building on the initial work of TWI2050 these authors reformulated the original Six Transformations, specifically subsuming consumption and production into the Decarbonization and Energy transformation and splitting the Human Capacity and Demography transformation into 'Education, Gender and Inequality' and 'Health, Wellbeing and Demography'.

Box 1. Key messages of the Six TWI2050 Transformations.[a)]

Substantial advances in human capacity are needed through further improvements of health care and education. Health and education are instrumental for enabling people to live a self-determined life, find decent work, and generate income to sustain themselves, but also to undertake climate change mitigation and adaptation 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 large savings potential 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 and sufficiency, increasing the share of renewable energy, electrification, and carbon capture and storage all play a key role in decarbonizing the energy system around 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 and at the same time limit the food system's environmental impacts by combinations of increasing agricultural productivity, reduction of waste and losses, and changes 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 obesity in the world.

Transforming our cities will benefit the majority of the world population. Pathways show that by 2050 around two thirds of human population will live in urban areas. Sustainable cities are characterized by high connectivity and 'smart' infrastructure, enabling high-quality services, with low environmental footprint. Transforming slums into decent housing is feasible with 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 (STI) are a powerful driver but the direction of change needs to support sustainable development. The Digital Revolution symbolizes the convergence of many innovative technologies, many of which are currently ambivalent in their contribution 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. There is also a need to implement forward-looking roadmaps and governance structures that allow the mitigation of potential trade-offs of a STI revolution, particularly relating to its impact on the workplace, on social cohesion, and on human dignity.

a) Full descriptions of the Six Transformations can be found in TWI2050 (2018), available at www.twi2050.org.

mobilizes opportunities to accelerate and leverage the transformation toward sustainable development. Convergence of knowledge, technology, and society must be considered for ensuring solutions for the SDGs (Roco and 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 parts of a highly interconnected system—changes in one domain will inevitably result in changes, at varying degrees, in all the others.

1.3. Science, technology, and innovation for sustainable development

Science, Technology and Innovation (STI) are at the core of human development. Since the onset of the Industrial Revolution, they have contributed to explosive development, such as the doubling of life expectancy, providing secondary education for half of humanity, and wellbeing for billions. However, they have also brought about negative environmental and societal impacts. The global STI community can guide the science and technology enterprise built over the past 200 years, including values, policies, and systems, to support sustainable development.

While all negative externalities, exogenous impacts, and shocks cannot be anticipated, STI can and should focus on enabling and achieving the 2030 Agenda. Various agencies, including the UN Interagency Task Team on STI for the SDGs (UN-IATT), the UN-science advisory committee, research institutes such as IIASA, organizations like the World Bank (WB), Organisation for Economic Co-operation and Development (OECD), and the European Union (EU), and individual countries, such as Japan, the Republic of Kenya[3], and the Republic of Serbia, have been developing, analyzing, and proposing new thoughts, frameworks, and methods for the STI ecosystem to promote innovation, efficiency, and sufficiency for the achievement of SDGs (e.g., the Global Pilot Programme on STI for SDGs Roadmaps,[4] GSDR 2019, TWI2050 2019, Mission-oriented policy

3 For readability, only 'Kenya' will be used in the remainder of this report.

4 https://sustainabledevelopment.un.org/partnership/?p=33852

Box 2. Global Sustainable Development Report 2019. The Future is Now: Science for Achieving Sustainable Development.

The Future is Now: Science for Achieving Sustainable Development, is the first Global Sustainable Development Report (GSDR) prepared by the Independent Group of Scientists appointed by the United Nations Secretary-General. The mandate, defined by UN member states, was to provide an integrated perspective on the state of sustainable development, to make available scientific knowledge on solutions and accelerated actions, and to strengthen the science-policy interface. The report was officially presented at the quadrennial SDG summit during the 2019 HLPF where UN member states acknowledged that decisions based on science must play a major role in advancing sustainable development.

The GSDR 2019 highlights the essential importance of science to understand and navigate relationships among social, environmental, and economic development objectives. It proposes three essential steps to support the implementation of the 2030 Agenda:

- Build on a systemic understanding of SDG interactions: The GSDR 2019 calls for systemic thinking to deal with the complexity of SDG interactions. It argues that understanding the interconnections between the individual SDGs is essential to manage difficult trade-offs and harness synergies to devise coherent policies and effective interventions.
- Address systemic entry points: It offers actionable intervention opportunities via six entry points to transform the key systems that define society today. These are congruent to the six TWI2050 Transformations: i) human wellbeing and capabilities; ii) sustainable and just economies; iii) energy decarbonisation and access; iv) food systems and nutrition patterns; v) urban and peri-urban development; and vi) global environmental commons. The main difference is that the sixth TWI2050 Transformation focuses on one global common, namely digitalization. Both reports call for transformational change for achieving the 2030 Agenda.
- Deploy key levers for sustainable development: The GSDR categorizes four levers of action: i) governance; ii) economy and finance; iii) individual and collective action; and iv) science and technology. While the GSDR outlines the abundant transformation knowledge available for these levers it also underlines that pathways to sustainable development can only emerge from combinations of such levers that respond to development challenges and priorities of specific local contexts.

This is where innovation has its place. While all levers—from science and technology, to governments, the private sector, and society—are important means to serve the purpose of sustainable development, no one represents a silver bullet. The key innovations needed are new alliances between these sectors, and related actors must hence radically rethink their partnerships to overcome their silos.

Such innovations are also required from science: while the report underlines the importance of stronger science-policy-society interfaces (see Chapter 4), it also makes the case for shifting current research priorities and supporting innovative approaches to sustainability science, emphasizing inter- and transdisciplinary partnerships, and committing support and resources to scientific institutions, particularly in the global South. Additionally, development aid budgets should prioritize boosting scientific capacity and access in the global South.

analysis, Smart Specialisation Strategies[5] and Society 5.0[6]; see Chapter 3 and its Section 3.2.4 and Chapter 4 and its Section 4.2.4 on sufficiency).

For innovation to play a major role in achieving the Six Transformations, it is necessary to understand what innovation actually is and the processes by which new innovations, whether technological, societal, institutional, or cultural, are adopted and implemented throughout society. This is discussed in detail in Chapter 2.

1.4. The paradox of innovation

Innovation, as a collective learning process, has been at the core of human progress since the dawn of civilization. Few other species are known to have learned to use tools. Human progress is the result of key innovations such as language, the harnessing of fire, and development of tools that culminated in the Neolithic Revolution. The explosive and purposeful direction of innovational change leading up to and during the Industrial Revolution, with the invention of the printing press, trades, banking, and the establishment of technical schools and universities, fundamentally changed our settlements, families, societies, and the way we live, work, and interact with each other. The 'Great Acceleration' following the Second World War brought about a new era in human history, the age of the Anthropocene. A period in which one species dominates the planetary processes and has ever-increasing awareness of its responsibility for stewardship of the Earth and its own future.

The 'paradox of innovation' is that it is both at the core of human progress and a major cause of human interference with the environment and planetary processes. At the same time, innovations in the broader sense will provide many possible solutions for achieving a sustainable future for the people and the planet.

Efficient transformations to sustainable and resilient futures minimize the environmental harm or impact through innovations (e.g., by lowering the energy use or material requirements of a product or

5 https://s3platform.jrc.ec.europa.eu/what-is-smart-specialisation-

6 https://www.japan.go.jp/abenomics/_userdata/abenomics/pdf/society_5.0.pdf

service). It guides innovations (with micro and macro perspectives) that anticipate and integrate short-term and long-term effects. This is to avoid the risk of overall unintended effects that may cause an increase of harmful environmental and/or social impacts, ideally through successively empirically informed feedbacks to the societal discourse. The diffusion of innovations (e.g., ideas, technologies, or policies), including dematerialized societal innovations, can contribute to a more sustainable future for all, as envisioned by the UN 2030 Agenda and its SDGs or the Paris Agreement (UNFCCC 2015).

Martin Heidegger (1977) argued that "innovations [and technology] are … [a means to an end] [and] a human activity" or means to a human end. This concept can therefore be called the instrumental and anthropological definition of technology and in a broader sense innovation in general. The 2030 Agenda could, in the same sense, be seen as an anthropologically oriented and influenced conceptual sphere concerned with key factors dealing with human existence in a safe, just, and equitable world. So, it is about the future of humanity for which integrity of Earth systems is essential. It is fitting in the age of the Anthropocene that humans, as the current drivers of planetary change, are charged with the responsibility of ensuring both their own and planetary sustainability.

1.5. COVID-19: risks and opportunities for a sustainable future

The COVID-19 pandemic is a major immediate threat to humanity, especially for those with previous health risks and those living directly deprived through poverty and lack of health care, but at the same time presents an opportunity to redirect our focus on what is important to us as a society, to redirect trillions of dollars of intended public financing toward investments into innovative activities for achieving a sustainable future for all. STI is the main strategy for long-term pandemic protection and control, with scientists around the world cooperating to develop treatments and a vaccine for COVID-19. Once successful and approved, which could potentially take 12–18 months, there needs to be a huge upscaling of production and distribution technologies to effectively protect the health of everyone. Innovation will be required in health care systems for more effective early response strategies, protection for all, including the billions who do not have health insurance, appropriate protection of doctors and nurses, and adequate levels of intensive care capacity in hospitals. In the meantime, the main mitigation strategies include social distancing and contact tracing, including through mobile-phone apps. This also requires institutional and organizational innovations as continued lockdowns are already having drastic negative economic and social consequences, especially for those without adequate insurance or savings to pay rent and purchase food and other necessities while unemployed.

It is clear that there are possible environmental and Earth-system benefits to the partial shutdown of the global economy. Some of the 'old' resource-intensive, inequitable and unsustainable characteristics of the global economy may be destroyed. There are declines in greenhouse gas (GHG) emissions and in air and water pollution. Societal benefits include declines in road accidents and fuel use from mobility reductions, materials use is down meaning less life lost in mining, and so on. The opportunity should not be lost to ensure that emerging employment and human activities be directed at achieving the sustainability transformation for people and the planet.

The list of negative societal consequences is very long, including adverse consequences for physical and mental health as a result of families being locked in their homes often without the possibility of being able to exercise outdoors or interact in social settings. There are reports of loss of education for children, and multiple burdens for the many working at home while taking care of children and other responsibilities. Another possible legacy of COVID-19 could be an increase in the challenges to achieving gender equity and empower all women and girls (SDG5). In the short term, stay-at-home orders can reinforce old stereotypes, with an increase in women's home responsibilities, including domestic activities, caregiving, and home schooling of children. These also increase demands and stress on women employed outside the home, whether in the formal or informal sector. The extent to which these changes will have longer-term consequences will depend on the length (and frequency) of these orders. In the short term, for example, limiting work often limits economic opportunities (Wenham et al. 2020).

While there is great uncertainty in predicting exactly what the economic damage from the global coronavirus pandemic will be, there is widespread agreement among economists that it will have severe negative impacts on the global economy. According to this year's World Economic Outlook (2020), global growth in 2020 is predicted to fall by 3% under the assumption that the pandemic and required containment peaks in the second quarter for most countries in the world, and recedes in the second half of this year (a downgrade of more than 6 percentage points from the economic growth forecast). With the world economy valued at US$136 trillion[7] (measured at international purchasing power parity) in 2018, this represents a systemic loss of about $4 trillion to $8 trillion—or 5 to 10 times the average global losses from current climate-related and geophysical disasters (World Bank 2020).

7 $ refers to US dollars throughout this report.

The proposed economic rescue plans already range in the trillions of dollars. Most are directed at preserving employment, which is absolutely necessary. However, one should ask the question whether some of the financing should be directed toward the Six TWI2050 Transformations to induce innovations and new lifestyles and norms toward sustainability for all. In fact, the danger is that these huge financial resources would be sprinkled in 'helicopter' style and would reinforce the current unsustainable practices and trends—maintaining the old and avoiding the new.

The Six Transformations offer essential STI synergies to achieve a new direction of development at lower cost while supporting the most vulnerable who will suffer the most, in the short and long term, in the absence of appropriate strategies. Just consider the four largest refugee camps in Kenya, the largest in the world, with close to 350,000 inhabitants, followed in size by camps in Hashemite Kingdom of Jordan, the Republic of South Sudan[8], the United Republic of Tanzania, Federal Democratic Republic of Ethiopia, and the Islamic Republic of Pakistan[9] (UNHCR 2020). The top refugee hosting countries are Republic of Turkey, Pakistan, Republic of Uganda, South Sudan, and the Federal Republic of Germany[10] (UNHCR 2020). Think of the millions of people suffering from the impacts of natural disasters, war zones, or climate change. Keep in mind the millions of children who do not have the chance to go to school. This is where some resources need to go, namely to those with worse starting conditions, little or no backup, little education, no jobs, and no safety nets.

Piketty (2019) proposed that every person in the French Republic[11] should receive 120,000 Euros at the age of 25 to enable innovative initiatives among those who lack the capital to do so. This would provide more equal opportunities to everyone. Even in Germany, an affluent country with exemplary social systems and universal health care, the bottom half of the population own only 3% of the capital (Piketty 2019). The current system, and one may soon say the 'old' system, is not resilient and in many ways inadequate in responding to the crisis caused by COVID-19. Part of this results from the increased inequity in income, wealth, and opportunities, and lack of health care and social security benefits for all. The vast majority of the global population lack the capital needed for innovation as they persistently live from 'hand to mouth' and fight for survival.

There is talk of what the 'new normal' may look like after the pandemic. It is unlikely that life will go back to the same. In addition to obvious changes that need to be made to global health systems and preparedness, practices resulting from social distancing requirements such as remote working and telecommuting, online schooling, e-commerce, local sourcing, etc., will become more common. As such changes become more widespread, there will be significant opportunities to accelerate the necessary long-term transformative changes toward sustainability. However, the risk is that exactly the opposite will happen, with governments and vested interests eager to return to a business-as-usual agenda. Another important risk is a political shift toward totalitarian governance and the notion of 'my country first.'

The COVID-19 crisis has finally alerted the world to the risks of biological shocks, not only in terms of human health but also in terms of their cascading economic and social consequences. The crisis raises profound questions about the resilience of sustainability transformation and the role that catastrophic systemic risk can and will have on reaching the SDGs in general, and specifically on the Six Transformations. To what extent can systemic shocks like COVID-19 set back progress: will systemic and catastrophic shocks mean that we risk taking *one step forward and two steps back* in meeting the SDGs?

The global scale of the coronavirus is unprecedented in recent history; yet, it can be argued that at the regional, national, and local scales climate-related and geophysical disasters have had an equally or more devastating human and economic toll, significantly setting back development in many of the most vulnerable countries.

In the recent two decades (1998–2017), climate-related and geophysical disasters killed 1.3 million people—about 65,000 annually—and left a further 4.4 billion injured, homeless, displaced, or in need of emergency assistance (Hallegatte et al. 2017). The mortality incidence of these non-pandemic events has been far more serious in highly vulnerable developing countries, where an average of 130 people per million have died compared to just 18 in high-income countries. In sharp contrast, COVID-19, at the time of writing (5 June 2020), has struck many countries both poor and wealthy, with mortality at 600 per million in the UK[12], 300 per million in the United States of America[13],

8 For readability, only 'South Sudan' will be used in the remainder of this report.

9 For readability, only 'Pakistan' will be used in the remainder of this report.

10 For readability, only 'Germany' will be used in the remainder of this report.

11 For readability, only 'France' will be used in the remainder of this report.

12 For readability, only 'UK'will be used in the remainder of this report.

13 For readability, only 'USA' will be used in the remainder of this report.

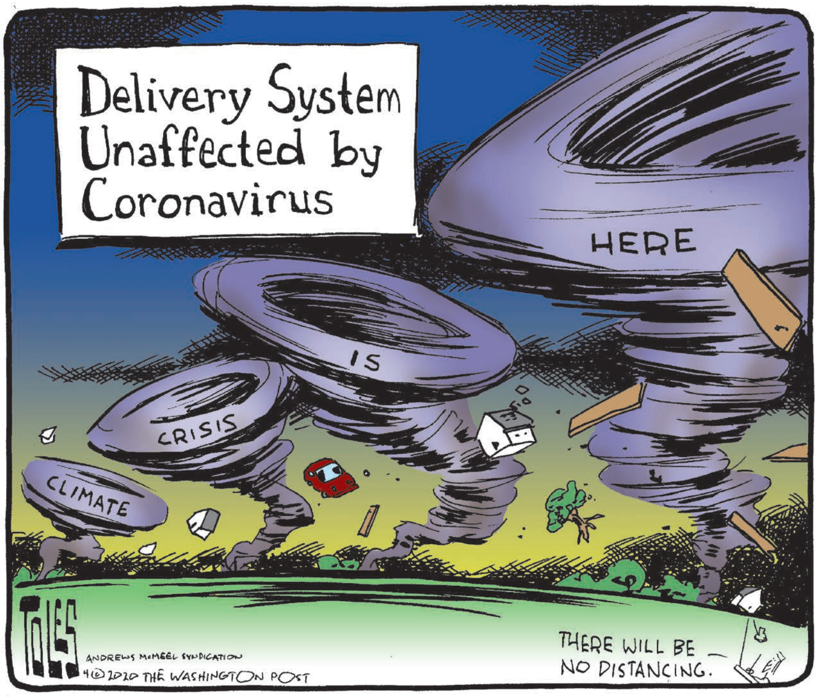


Figure 2. The cartoon illustrates that despite the major immediate threat of the COVID-19 coronavirus, there are other delivery systems unaffected. The climate crisis is here and also injustice, inequity, and ever-increasing pressure on Earth systems and global commons. Source: TOLES © The Washington Post. Reprinted with permission of ANDREWS MCMEEL SYNDICATION. All rights reserved.

over 550 per million in the Republic of Italy[14], 200 in the Republic of Ecuador, over 160 in the Federative Republic of Brazil, and 3 per million in the People's Republic of China[15]—with a global total of more than 300,000 (JHU 2020). How the pandemic unfolds in the following months is still to be seen.

In this same two decades, non-coronavirus disasters—according to the WB—led to real losses to the global economy up to a staggering $520 billion per annum, with disasters pushing 26 million people into poverty every year (Hallegatte et al. 2017).

The COVID-19 crisis adds emphasis to the historical evidence that catastrophic and systemic risk from natural and biological causes can greatly set back progress on the Six Transformations needed for meeting the SDGs. Prevention pays, yet history tells us that societies do not take the risk mitigation measures necessary to clear the way for progress. A transformation in disaster risk management that takes a more positivist and holistic approach and shifts significant efforts and resources to mitigating disaster risk, appears to be a prerequisite for meeting the SDGs. Health has finally been acknowledged as a global commons. So far humanity has not excelled at safeguarding the commons. Maybe the COVID-19 crisis is both a wake-up call and a training ground to enhance our joint and resilient response to future pandemics and other external disturbances. This is only the first of many possible future pandemics to come if we continue on an unsustainable development path.

1.6. Outline of this report

This report focuses on how innovation, and STI more broadly, can both drive and facilitate the TWI2050 Six Transformations toward a sustainable future.

Chapter 2 considers what innovation actually is, and the processes by which innovations, whether technological, societal, institutional, or cultural, are adopted and diffuse. Such an understanding is fundamental for any attempt to direct or socially 'steer' innovation toward sustainability. Chapter 3 provides examples of the types of innovations required within and across the Six Transformations, with an emphasis on efficiency and sufficiency for enhancing prosperity for all. It is about 'doing more with less.' Finally, Chapter 4 discusses the innovations required in governance, institutional, and societal structures and practices, across scales, to help guide these innovations to achieve the desired, just, and resilient sustainable future for people and planet.

14 For readability, only 'Italy' will be used in the remainder of this report.

15 For readability, only 'China' will be used in the remainder of this report.

If I had asked the public what they wanted,
they would have said a faster horse.
Henry Ford (1863–1947)

2 Invention and innovation for sustainability

2.1. A new look at the process of invention and innovation

Our societies, globally, are currently experiencing a 'double whammy'—the conjunction of a short-term and a long-term disruption in their customary dynamics. The reaction to both of these is significantly different—the societal reaction to the long-term disturbance, the sustainability conundrum, is at best hesitant and often a case of denial after some 30 or 40 years of exposing it, and its potential consequences. Yet the reaction to the short-term crisis—the COVID-19 pandemic—though initially hesitant, is now reaching its full defensive momentum. There are many interesting scientific questions concerning this difference. Questions that may have an important impact on the future of human behavior and organization.

One such question concerns the role of invention and innovation. We often hear, in the sustainability context, politicians, consultants, and others utter the phrase, "We have to innovate our way out of the challenge!" or "We should not waste a crisis!" whenever they have no answer to questions put to them by civil society. However, they often fail to recognize that 250 years of unbridled invention and innovation since the Industrial Revolution have landed us in this predicament. History matters. In this chapter, we will try and provide a fresh look at the role of invention and innovation in our current socioeconomic-environmental system dynamics to show why STI are the key for achieving the Six Transformations and thus the 2030 Agenda, provided they are handled more carefully than has been customary to date.

History and background

Inventions and innovations have always been a characteristic of human societies, with an acceleration after the Industrial Revolution. Why? Girard (1990) and Beckert (2016) argue that around the time of the Enlightenment and the Industrial Revolution in Europe, an important change in perspective occurred. Until that time, they argue, the future was viewed as being circular in the sense that "it was more of the same as had occurred in the past," while a new distinction was made in that the future is "the time in which change can occur." Looking at the past (ex post) was increasingly distinguished from looking at the future (ex ante). However, science was slow in adopting that perspective. For example, to be admitted into the community of recognized scientists of the Royal Society in London, one had to demonstrate or prove one's scientific statements. As this could not be done for the future, for career reasons, scientists increasingly focused on looking for the origins of the present by focusing on the past. One could argue that it is only with the adoption in the 1970s of the so-called 'Complex Adaptive Systems (CAS)' (Mitchell 2009) perspective that scientists developed tools to look at the future by focusing on the emergence of phenomena.

A CAS is a system in which a perfect understanding of the individual parts does not automatically translate to a perfect understanding of the whole system's behavior (Miller and Scott 2007). In CAS, the whole is more complex than its parts, and also more complex than the aggregate of its parts (Holland 1998). The study of CAS is highly interdisciplinary and brings together insights from the social and natural sciences to develop system-level models that allow for heterogeneous agents, phase transition, and emergent behavior (Auerbach 2016).

This change had important consequences for STI. In the CAS approach, one can, at least theoretically, focus scientifically on the process of innovation and change, rather than relegate invention and innovation to the scientifically untreatable black box of 'creativity' as was done in the era of reductionist science. Therefore, we adopt the CAS approach to the study of innovation. In doing so we hope to contribute to a trend of scientific and systems-based decision making that is increasingly called for in civil society and business (OECD and IIASA 2020).

Multiple futures, ontological uncertainty, and unintended consequences

Like every scientific approach, CAS has its own strengths and weaknesses. A great strength of this approach is that it acknowledges the inherent complexity of most socio-environmental dynamics. Rather than reduce the full complexity of their interaction to a chain of cause and effect playing out in a few dimensions, as the reductionist approach does, the CAS approach views the emergence of novel phenomena as part of their multidimensional trajectories and thus does not simplify systems dynamics as much as the reductionist approach does. It follows also that the CAS approach always considers multiple future states of any phenomenon studied.

An apparent disadvantage, that is often cited, is that using the CAS approach makes it more difficult to predict the evolution of systems dynamics over the short and the long term. But in our opinion that is erroneous, as the linear, reductionist, cause and effect does indeed make both short- and long-term predictions, but these are not necessarily more accurate. Instead, the CAS approach increases the accuracy of short-term predictions while performing no better on long-term ones. As Lane and Maxfield (1997) argue, the CAS approach acknowledges that the future is ontologically uncertain.

Due to limitations of humans' short-term working memory, the perception humans have of any phenomena occurring in the external world is highly reduced in its dimensionality and thus also biased. But when human beings act in the environment based on these perceptions, the simplified perceptions are confronted with the full complexity of the external world. As a result, any action has many more consequences in the wider environment than can be perceived. Unforeseen and unintended consequences result from all human actions, including inventions and innovations (Huesemann and Huesemann 2011). The paradox of innovation is that it can resolve many perceived problems but in doing so, often creates unforeseen and unintended ones.

The need to improve control over invention and innovation

As our societies are envisaging that innovation "will get us out of trouble," even though we would argue that the 250 years of innovative progress since the Industrial Revolution have got us into trouble—as humanity transcended many of the planetary and environmental boundaries while at the same time providing many benefits to humanity—we do not conclude that we must stop all innovation and aim for an undifferentiated no-growth economy without change. We think continued growth might be attained by growing in a dematerialized manner, emphasizing social and technological innovation. But that means one would have to be able to steer innovation. There are at present a number of barriers to doing so. The first of these is the nature of our current economic and financial systems, that are now so widely embedded in our societies that it is difficult to change. Although a pandemic such as COVID-19, which occurs against a background of increasing evidence of partial dysfunctionality of the system, might contribute to moving it in a different direction.

Does one favor automation over employing people? Or does one favor protecting people from the COVID-19 pandemic over keeping them employed? The choice involves many different aspects of our current path-dependent socioeconomic structure. For example, continued automation might lead to a point where most of our human needs can be met technologically (TWI2050 2019), but societies would have to deal with a large proportion of unemployment, unless the overall population size declines to the numbers needed for the service economy, or the system is being changed to one based on basic income for all irrespective of employment to avoid major societal conflict (Arthur 2015). Either solution would have major unintended consequences and would represent a fundamentally different future development pathway. Such changes are only possible over the long term, and in view of the difficulty of taking long-term decisions in democratic systems, they may simply be impossible to implement on large scales. So we have to think in terms of cumulative incremental change. But who decides on how this might be achieved? In the past, fundamental changes have been disruptive and discontinuous such as the new development pathway that followed the Great Depression of the 1930s.

Another barrier to steering innovation is the fact that we have no accepted scientific ideas about how invention occurs. We need to distinguish here between invention (the act of creating something new) and innovation (the act of introducing that invention in society and spreading its use). We know a lot about innovation in society and how to promote it (Nakicenovic and Grubler 1991, Grubler 2000). Economists have widely studied both the conditions for stimulating invention and the result of innovation for the economy (Rosenberg and Nathan 1982, Rosenberg et al. 1992, Rosenberg 2000), but because reductionist science has, as mentioned above, considered creativity as a 'black box' (Rosenberg and Nathan 1994), we still do not really know whether we can really steer invention, let alone how to do so beyond 'freeing the animal spirits,' by asking certain questions and funding research to answer them. Only by gaining a better understanding of the process of invention itself may we hope to gain more control over it, and thus enable our societies to focus it in certain directions. New insights might emerge from the current exceedingly high premium for new means to combat COVID-19.

A third issue is the question, who is, or who should be, involved in invention and innovation? If we do not want the current 'freedom of invention and innovation' to continue as is, but would like to mobilize invention and innovation toward certain goals (such as sustainable development), how could that be implemented? For example, if the precautionary principle were to be elevated to a prime goal of invention and innovation, which kind of political or administrative structure would that require? How would one involve the general public in this, so as to improve its trust in the policies introduced in that context?

A related issue is the question of control over inventions and innovations. The Information Revolution has fundamentally changed our perspective on invention, from something achieved by a few individuals in isolation, to an awareness that invention is a systemic phenomenon that involves many people in a network, with both strong and weak ties among them. This posits the question, who can 'own' or 'control' an invention? In other words, is our current system of patents and trademarks adapted to the new situation?

The roles of technology and economy in the evolution of our societal systems

For a long time, the accepted vision among economists was that technology adapted itself to the economic conditions of a society. However, if one does not merely consider individual inventions, but the underlying logic that is responsible for them, and which is relatively stable, the inverse can also be argued (e.g., Arthur 2009). In many ways, that seems to be a more productive way to look at the relationship, especially at a moment in time at which there is a clear shift in applications for patents, from those that generate new technologies to those that combine existing ones (Strumsky and Lobo 2015) or are acquired to protect against competition.

But can either the current Western capitalist economy or its technology continue to develop, or are there inherent barriers to their continued growth and expansion? In economics, numerous dissenting points of view developed in a sustainability context argue that that is not the case. For technology, a similar argument can easily be made (van der Leeuw 2020, Zhang and van der Leeuw in press).

Hence, there is a need to introduce a fundamentally different socioeconomic approach, which does not oppose nature and culture, but builds on the relationship between the two to escape the current conundrum. That is what the other chapters of this report will be dedicated to.

2.2. Technology, social, institutional, and cultural innovation

Innovation must be viewed as a complex system in which all components, technology, society, institutions, and culture work interactively and holistically to bring about widespread transformative change. Innovation in one component will necessarily lead to innovations in all others if the innovation pathway is to succeed. Similarly, a failure to bring about innovation in one component can lead to overall failure. For example, autonomous vehicles are undoubtedly a groundbreaking technological innovation; however, without the necessary accompanying innovations in societal and cultural acceptance and regulatory frameworks they are likely to be reduced to a novelty or even an abject failure. As such, it is meaningless to discuss each of these components independently in the context of this report and the overall sustainability transformation. However, given that the processes of technological innovations have a long history of research, an examination of these processes can be relevant to understanding innovation more generally, and hence are a major focus in what follows. However, where relevant, the other components of innovation are highlighted.

Technology innovations

Innovation is most simply conceived of as novelty, originating from human endeavor and inspiration. Technology innovations range from radical new inventions to marginal performance improvements and encompass social and behavioral changes alongside new technologies reflected in innovative processes, products, and institutional change. Innovations that are successful typically undergo widespread diffusion, upscaling, and commercial uptake. But this outcome is the culmination of an often-lengthy process which runs from research and development through demonstration and trials to early market formation and then diffusion. There are countless pitfalls along the way. The process is characterized by deep uncertainties—one can say that "many are called but few are chosen." The majority of innovation journeys end in failure, some abject, others marginal. Innovation is neither costless nor determinate. Even successful innovators often have a history of failures that are important learning experiences for the eventual adoption. This renders study of the innovation process difficult because mostly successes are recorded followed by pervasive diffusion while failures, with a very few exceptions, are forgotten.

What is technology? Grubler (1998) points to the Greek origin of the name composed of τεχγε (techne—art, the practical capability to create something) and λογοσ (logos—word, human reason). Thus, τεχγε λογοσ (technologia) is the science and systematic treatment of the practical. In a most general sense, technology is a system of means to a particular purpose that employs both technical artifacts and social information—often referred to as know-how and know-why. In the narrowest sense, technology consists of manufactured objects like tools (axes, arrowheads, and robots and software as their modern equivalents) and infrastructure or containers (buildings, pots, water reservoirs). The purpose is either to enhance human capabilities (e.g., a hammer can apply a stronger force to an object) or to enable humans to perform tasks they could not perform otherwise (a pot can transport larger amounts of water than your hands). Engineers call such objects 'hardware.' Anthropologists speak of 'artifacts.'

But technology does not end there. Artifacts have to be made. They have to be invented, designed, and manufactured. This requires a larger system including hardware (such as machinery or a manufacturing plant), factor inputs (labor, energy, raw materials, capital), and finally 'software' (know-how, human knowledge, and skills). The latter, for which the French use the term 'technique,' represents the disembodied nature of technology, its knowledge base. Thus, technology includes both what things are made and how things are made. In that sense, technology is cumulative and a learning process. Changes build upon previous experience and knowledge and the stock of knowledge grows continuously.

Finally, knowledge, or technique, is required not only for the production of artifacts, but also for their use. Knowledge is needed to drive a car or use a bank account. Knowledge is needed both at the level of the individual, in complex organizations, and at the level of society. A typewriter, without a user who knows how to type, let alone how to read, is simply a useless, heavy piece of equipment. In the case of a smartphone or a laptop, knowledge plays the essential role to render the use possible. Technologies also have to fit into a system. Laptops or smartphones are useless without the systems in which they operate such as the Internet or the Global System for Mobile (GSM) Communications system and their associated network infrastructure. Despite the immense complexity of the systems and devices, the knowledge needed to operate a phone or laptop need not necessarily encompass understanding the technical or software dimension of the underlying technologies of the devices themselves.

Humans, of course, process matter (food, raw materials, etc.), energy (transportation, heating, lighting, etc.), and information (facts, stories, but also sound, smell, touch, or images). The first two of these are necessary for physically sustaining us as individuals. However, information is different. It is not concerned by the conservation principle, and therefore it can be shared. It is therefore the 'cement' that brings and keeps societies together by sharing values, ideas, customs, and institutions.

Over the long term, the ways in which individuals and groups process information determines their organization, their values, their ideas, their categories, their institutions, and their technologies. All these aspects of social life are dependent on information processing, and the evolution of that processing over time has driven the coevolution of all the above aspects of societies, from the small groups of hunter-gatherers in the Paleolithic to the complex societies of the present.

With respect to innovation, particular attention needs to be paid to the relationship between information processing and technology. Not only are all artifacts, from simple stone axes to nuclear reactors, the result of information processing and the decision making that is based on it, but they are also information processing tools in their own right. The complex mechanisms of a car, for example, exonerate the user of the vehicle from knowing all but the most basic information about how the car works, and thus frees a substantive amount of information processing power, leaving the owner only the task of driving it. Similarly, a saw limits the information processing that is needed to cut a tree by fixing a number of the decision parameters (such as the angle to hit the tree with an axe) and confining the cutting to pulling back and forth along a fixed line. We conclude that technology (and thus innovation and invention) are an externalized part of a society's information processing apparatus.

Technological hardware varies in size and complexity, as does the 'software' required to produce and use hardware. The two are interrelated and require both tangible and intangible settings in the form of spatial structures and social organizations. Institutions, including governments, firms, and markets, and social norms and attitudes, are especially important in determining how systems for producing and using artifacts emerge and function. They determine how particular artifacts and combinations of artifacts originate, which ones are rejected, or which ones become successful, and, if successful, how quickly they are incorporated in the economy and the society.

Unintended consequences of invention and innovation

When an innovation starts diffusing, it calls forth novel arrangements and organizational forms. The new technology or new arrangements in turn may cause new problems. These in turn are answered by further novel arrangements (or by existing technologies modified for the purpose), which in turn may open the need for yet more novel technologies. The whole system moves through a learning process forward in a sequence of problems and their solutions—of challenge and response—resulting in structural change. In this way the economy forms and re-forms itself in spates of change, as novelty, new arrangements to accommodate this, and the opening of opportunity niches follow from each other.

Bringing such systems dynamics to a halt is difficult and in practice often impossible. We have been stressing that every solution in the form of a new technology creates some new challenge, some new problem. Stated as a general rule, every technology contains the seeds of a problem, often several. This is not a 'law' of technology or of the economy, much less one of the universe. It is simply a broad-based empirical observation—a regrettable one—drawn from human history. The use of carbon-based energy sources has increased widespread economic efficiencies but resulted in global warming. The use of atomic power, an environmentally clean source of power, has brought the problem of disposal of atomic waste and danger of catastrophic accidents. The use of the chemical DDT was a marvelous advance for agricultural pest control but led to widespread health and environmental problems. The use of air transport has brought the potential of rapid worldwide travel and commerce but also the spread of infections and pandemics. In the economy, solutions lead to problems, and problems to further solutions, and this dance between solution and problem is unlikely to change at any time in the future. If the diffusion leads to the solution of negative externalities of technology adoption, a net individual and social benefit results that we call progress. Whether or not progress exists and how long it lasts condemns innovation—and the society and economy as a result—to continuous change.

Evolution and diffusion of innovations

Schumpeter and Redvers (1934) distinguished three important phases in technological development: invention, innovation, and diffusion.

Invention is an empirical or scientific discovery of a new principle or a principal feasibility of a proposed solution. It can also be a new linking of existing needs, purposes, and effects. It rarely offers hints of a possible practical application. Invention is a lengthy process and not merely an accumulation of small changes. Inventions in one field can have large effects on the development of technology in other areas, leading to new technologies, processes, and new industries. Overall, as already mentioned, our knowledge about this phase is very limited and we need to study this scientifically to understand how we may be able to steer it.

Innovation refers to the first application of an invention to a practical purpose. Often, process and product innovations are distinguished. More generally, innovation can refer to new social processes or creation of new institutions. A key question assessed in this report is whether the direction and purpose of innovations can be 'socially steered' toward a sustainable future for all.

Every technological innovation stands on a pyramid of previously available technologies and any future innovations are derived from presently available technologies. Innovations happen through combinations of existing technologies. They serve opportunity niches based on human needs and come with accompanying needs for infrastructure, skills, and processes. This is a continuous problem-solution circle that is flexible and ever changing. Innovations, once they have successfully diffused, can lead to domino-like collapses of the old for new technologies and industries.

The third phase refers to diffusion—characterized by the widespread replication and adoption of the innovation throughout society. According to Rogers (2010) four main elements influence the diffusion of innovations: the innovation itself, communication channels, time, and the system. Once the innovation is widely adopted and has reached a critical mass, it can self-sustain. The diffusion of innovations is defined by temporal as well as spatial characteristics (Rogers 2010).

Diffusion is a transformative process characterized by improvements in many dimensions from costs to technical performance leading to competitiveness and eventual replacement of the 'old.' Other characteristics include increasing scale, variety, and complexity, division of labor and interdependence, interrelatedness and 'network externalities' (Grubler 1998). Figure 3 illustrates diffusion in three dimensions: intensity of adoption, in space and in time. Early adoption generally leads to more pervasive diffusion and the further from the center in space (this can be virtual space of spillovers

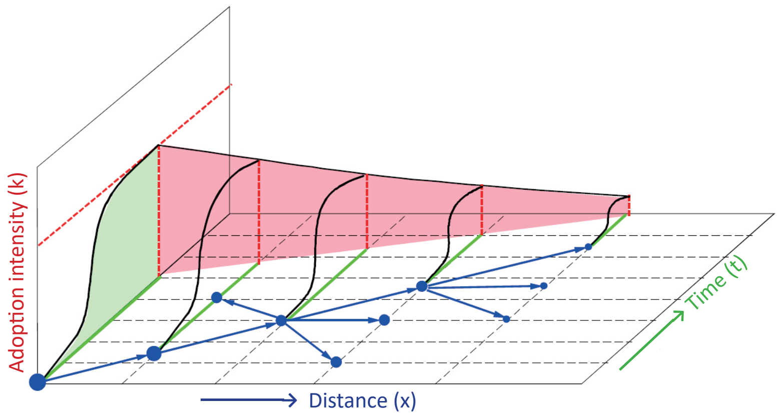


Figure 3. Spatial characteristics of diffusion. Diffusion tends to take more time in the case of early adopters than in the followers but adoption levels are higher in the core of innovation diffusion than in the periphery both in time and distance. Source: Morrill (1968).

or some other characteristics of the process), the later diffusion generally starts, is more rapid but leads to a lower level of adoption. These are some stylized but salient properties of the diffusion processes.

Ultimately, diffusion is a social and economic process as it encompasses mutual interactions of concurrent technological, institutional, behavioral, and social change. It is not a linear but rather a complex interactive process including 'bundles' or 'clusters' of technologies.

The essence of technological change and diffusion is in the 'new combinations' (Schumpeter and Redvers 1934), particularly those that are disruptive, discontinuous, and radical—combinations that cannot be achieved by gradual modifications of existing systems. Radical change through new combinations is rare and nonlinear in comparison with more gradual improvements. Examples include the internal combustion engine, automobiles, and petrochemicals to name just a few new combinations that radically and irreversibly changed economic structure, consumption patterns, regulatory mechanisms, and governance in general (see Box 3).

Innovations diffuse as the result of substantial performance and productivity increases as organizations and individuals gain experience with them. Such improvements reflect organizational and individual learning and social changes in general. Learning can originate from many sources. It can originate from outside an organization through the purchase of expertise or new processes or organizational structure. Or learning can originate from the inside through research and development (R&D) and investments in new technologies or organizational structure. Learning can also come through improving know-how, that is, learning how to make things better with the things themselves (artifacts, designs, practices, jobs, etc.) basically unaltered. Or learning can come through improving design features and economies of scale, reducing costs by building and using larger and larger units. There is, however, one strict precondition for learning. It requires effort and the actual accumulation of experience. It does not come as a free good. At the same time, it is one area of human improvement that is not exhaustible as far as we know.

2.3. Transformation through learning

Technological learning phenomena—long studied in human psychology—were vividly described for the aircraft industry by Wright (1936), who reported that unit labor costs in air-frame manufacturing declined significantly with accumulated experience. Grubler (1998) gives numerous examples of technological learning from manufacturing and service activities ranging from aircraft, ships, refined petroleum products, petrochemicals, steam and gas turbines, and even broiler chickens. Applications of learning models have ranged from success rates of new surgical procedures to productivity in kibbutz farming and nuclear plant operation reliability (Argote and Epple 1990, Grubler 1998). Learning and improvement through accumulated knowledge have been fundamental for human progress since the dawn of civilization and in principle are not limited like other activities. Learning is truly renewable and includes

Box 3. Innovation capabilities as a cross-cutting realm for upgrading societies' transformation capacities.

It should not be forgotten that innovation both pertains to various improvements of already existing solutions (both technical and societal) as well as brand new innovative 'jumps.' One example is the innovation to launch electrical cars. The innovation relates basically only to the motor side, not necessarily to the 'car' as a total technological system. However, this partial upgrading of the car opens up gradually for strong improvements of other kinds, for example, driverless cars, although the new artificial intelligence (AI)-computerized solution does not depend on the initial electric motor innovation. There could be even further technical steps such as some Le Courbousier visions about futuristic cities with helicopter-like vehicles zooming around in three-dimensional space. That is probably the step when you no longer talk about this transportation unit as a 'car' but rather something else.

There is another innovation step dealing with the social organization of the technical upgrading, for example, transportation solutions. This occurs when you no longer atomize the transport system to individual car units but embed the transportation function in a broader computerized system with different types of sub-vehicles that provide a distributed systems function for transport of both persons and goods. Still another step would be to reduce the societal need to move material entities around and support the function of meetings to online exchange of information with the participants working from home-based positions. Further steps include systems that could be inbuilt in human bodies (as is already starting to happen in techno-medical prosthetics) where the hardware for manipulating the robot arm is implanted and directly connected to the human nervous system.

Many of these advanced functions are already being linked in AI implementations using the knowledge space of vast databases (big data), such as, biometric and facial recognition technologies being connected to an individual's societal records. This also holds true for identification of market behaviors and/or the political preference potentials of individuals. This also incorporates measures to track the spread of viruses (e.g., the coronavirus) by using network information of people's movements. Thus, these techno-social innovations raise deep considerations of a cultural/normative nature—both positive and negative in character.

social, technological, economic, institutional, cultural, and behavioral dimensions in a holistic and integrative manner.

In economics, 'learning by doing' and 'learning by using' have been highlighted since the early 1960s (see e.g., Arrow (1962) and Rosenberg and Nathan (1982)). Detailed studies of learning track the many different sources and mechanisms (for a succinct discussion of 'who learns what?,' see Cantley and Sahal (1980)). Here we focus on the productivity gains from learning, which can be very large indeed. During the first year of production of World War II Liberty ships, for example, the average number of labor hours required to produce a ship decreased by 45%, and the average time decreased by 75%. Current examples range from photovoltaics, microchips, windmills, and many other technologies with learning rates in the range of about 20% (cost reduction per cumulative doubling of output). There are also cases, however, where no learning is evident, and we briefly discuss the reasons for such learning failures.

Innovation and radical and disruptive new combinations have the potential of substituting new for old practices. Learning processes are central for the rapid improvement of new combinations compared to comparatively slow and incremental improvements of the old. Examples are plentiful and include replacement of horses and carriages by motor vehicles, sailing ships by steamers, copper wire by mobile phones, or traditional corn by hybrid varieties. As mentioned, these processes should not be seen in a narrow technological sense but rather in their broader social, economic, institutional, cultural, and behavioral dimensions. Despite the enormous complexities and inherent differences of many of these transformational processes, there are some commonalities. Suffice it here to highlight the commonality of learning by doing or using. The new generally has much higher improvement potential in terms of fulfilling human needs, reducing some fundamental limits reached by the old such as environmental externalities (e.g., air pollution), substantive cost reduction, or ease of use, to mention just a few of the drivers of eventual replacement of the old. For example, the great manure crisis toward the end of the 18th century was a huge constraint on further expansion of the horse economy.

At the turn of the century there were some 15 million road horses in the USA (Nakicenovic 1990) and 100,000 horses on the streets of New York producing about 1,000 tons of manure per day, literally mountains of manure. London, Paris, and other growing cities shared this unsurmountable challenge. This attracted huge numbers of flies which then spread typhoid fever and other diseases. Add to that the liter of urine per day and large numbers of horse carcasses, this vividly describes the limits of the horse economy.

Therefore, it is not surprising that when motor vehicles arrived at the turn of the century, they rapidly replaced horses. In most of the leading economies around the world the substitution lasted about 30 years so that by the 1930s the process was essentially completed. Figure 4 shows the Easter parade on 5th Avenue in New York City in 1900 and 1915, respectively. In the former picture, only horses and carriages are visible and 15 years later only motor vehicles. This was a fundamental transformation of leading economies with deep changes in the industrial structure, employment, consumption patterns, institutions, regulation, behaviors, and so on. While it is true that motor vehicles produced unbearable

Figure 4. Easter parade in New York City on 5th Avenue in 1900 and 1915. Source: Adapted from Campanale, Carbontracker. 1900: National Archives and Records Administration, Records of the Bureau of Public Roads. Image 30-N-18827, https://www.archives.gov/exhibits/picturing_the_century/newcent/newcent_img1.html. 1915: Library of Congress Image LC-B2- 2529-9, hdl.loc.gov/loc.pnp/pp.print.

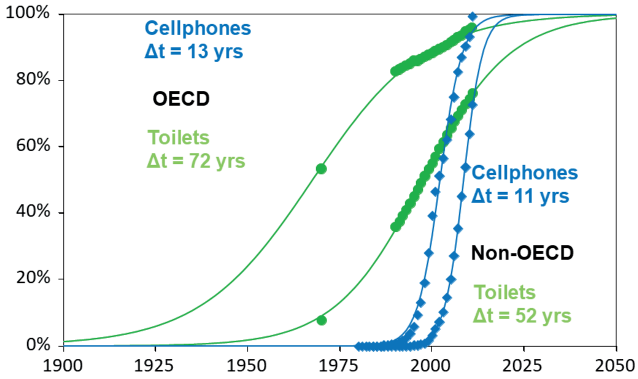


Figure 5. Digital technologies are spreading rapidly in developing countries. Technology diffusion comparison of cell phones and toilets for OECD countries and non-OECD countries. There are still about two billion people without access to sanitation and toilets while almost all have a mobile phone even though still close to a billion people do not have adequate access to electricity. Data source: World Bank WDI, CC BY. Source: Model fit and graphic courtesy of Arnulf Grubler, cfr. TWI2050 (2019), Figure 9.

smog and congestion once their numbers and densities increased by orders of magnitude some half a century later, originally, they were a solution to the unbearable negative environmental externalities of the horse economy.

Mobile phones, and more recently 'smart' phones, are another great example of disruptive transformations in the broader sense of human development. In merely three decades since their introduction, essentially everyone in the world now has a phone. There are 9.3 billion mobile phones for 7.7 billion people. However, there are close to a billion people who do not have access to electricity but still need a phone! When introduced in 1992, the first digital GSM phone, the Motorola International 3200, cost €6,300 (adjusted value) with a provider contract,[1] meaning it was essentially unaffordable. Today a good smartphone may cost more than a hundred times less. This is a breathtaking systems improvement in a very short time brought about by a combination of technological progress in phone design and performance, development of standards and pervasive infrastructure, and massive changes in human behavior, so that today a smartphone can replace some 50 analog devices. This comes not only at a fraction of the cost but also results in 100 times less energy and emissions, even the materials and embodied energy are about 25 times lower. Granular end-use technologies such as smartphones diffused much faster than other technologies, such as improved sanitation (Figure 5). Smartphones are used for banking, social networks, communication, selfies, and more recently as a most promising means of proximity measurement, namely social distancing, and contact tracing in fighting the spread of COVID-19.

1 https://de.wikipedia.org/wiki/Motorola_International_3200

A common feature of these rapid transformations is the enormous improvement across scales as the new diffuses through changes in technological, economic, social, institutional, cultural, and behavioral dimensions through learning processes. The effect of cumulative learning by doing and using is difficult to measure quantitatively. Failures are an important feature of innovations. Very few are successful, but most of the evidence describes winners and not losers. Qualitatively the evidence for learning is massive. One proxy is the costs of systems as a function of cumulative production or sales. As mentioned above, Wright (1936) measured the number of hours needed to assemble planes and showed that hours decreased dramatically as a function of cumulative shipments. It turns out that per doubling of cumulative shipments the number of hours required to make a plane (of the same type) declined by some 20%. Everyone has experienced this personally when acquiring new skills, be it typing, cooking, or writing scientific papers—with experience and learning it gets easier and less time is required.

Learning phenomena are described in the form of learning or experience curves, where typically the unit costs of production decrease at a certain rate. Unit costs decrease along an exponential decay function. Because learning depends on the actual accumulation of experience and not just on the passage of time, learning or experience curves are generally described in the form of a power function where unit costs depend on cumulative experience, usually measured as cumulative output.

Technological learning is a classic example of increasing returns, that is, the more learning takes place, the better a technology's performance. It is the technology counterpart of the increasing returns resulting from the accumulation of knowledge or increases in human capital that are the focus of endogenous growth theory (e.g., Romer (1986), Romer (1990); or Grossman and Helpman (1991) and as discussed increasingly also in the technology domain (cf. Arthur (1983), Arthur (1989)).

Granularity and rapid innovations deployment

Rapid deployment of innovation and replacement of the old by new combinations depends on short diffusion timescales, attractive risk profiles for investors, and strong potential cost and performance improvements through learning. These conditions are interdependent. Deployment generates experience, which feeds back into technology improvement. Improving competitiveness and reducing investment risk stimulate adoption and compress the time taken for technologies to diffuse through markets and be adopted across different users. Clear expectations for market growth attract further investment and strengthen the rationale for policy support (Wilson et al. 2020a). These dynamics are evident in recent trajectories of rapid solar photovoltaic (PV) deployment as showing in Figure 6.

Figure 7 shows the cost reductions of a number of consumer goods and larger-scale technologies such as power plants as a function of cumulative market (adoption) doublings. Large differences in the learning rates are portrayed. Figure 7 shows that learning is faster for more 'granular' systems and technologies (Wilson et al. 2020a) with the learning rate on average about 20% in terms of cost reductions per doubling of cumulative units produced. In contrast the 'lumpier,' large-scale systems and technologies portray on average significantly lower learning rates of about 10% per doubling of cumulative units produced. Some technologies like nuclear power plants display 'negative' learning rates, where the cost increases with increasing number of installed plants!

The notion of 'granularity' is used to describe technologies in terms of scale—physical, economic, or both—and often this is also reflected in institutional, regulatory, and other processes associated with the respective innovations. More granular innovations typically have smaller and more variable unit sizes (e.g., in case of energy in terms of MW/unit) and lower unit investment costs in absolute terms (e.g., costs/unit), and are more modular or divisible, so they are more likely to upscale through replication. In contrast 'lumpiness' refers to larger units, higher unit investment costs, greater indivisibility, and more likelihood of

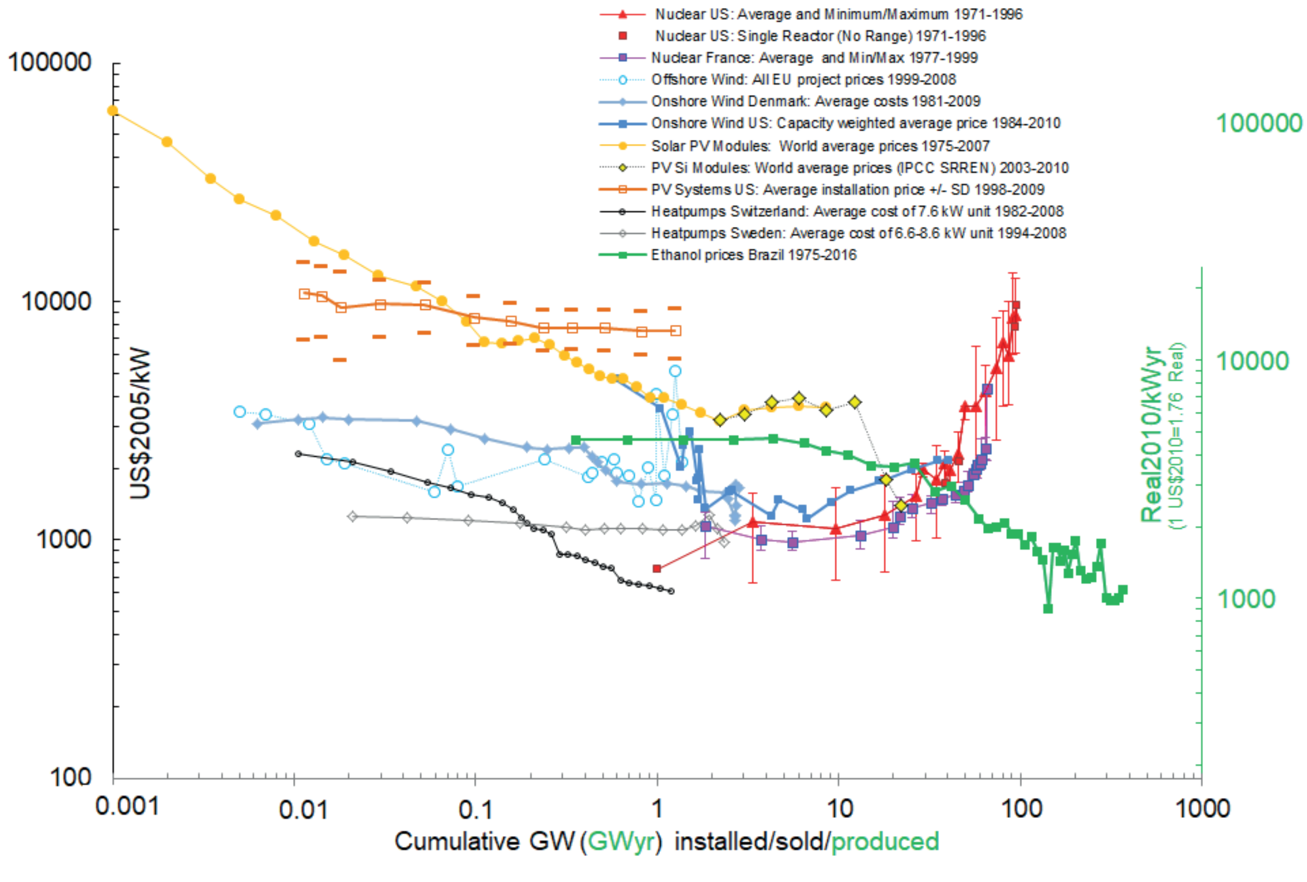


Figure 6. Learning curves for a number of technologies including global photovoltaics with demonstrated cost reductions of two orders of magnitude, onshore wind (Denmark) and bioethanol (Brazil). Source: Updated from GEA (2012), Chapter 24 by Grubler et al. (2012a) and Wilson and Grubler (2014). Graphic courtesy of Arnulf Grubler.

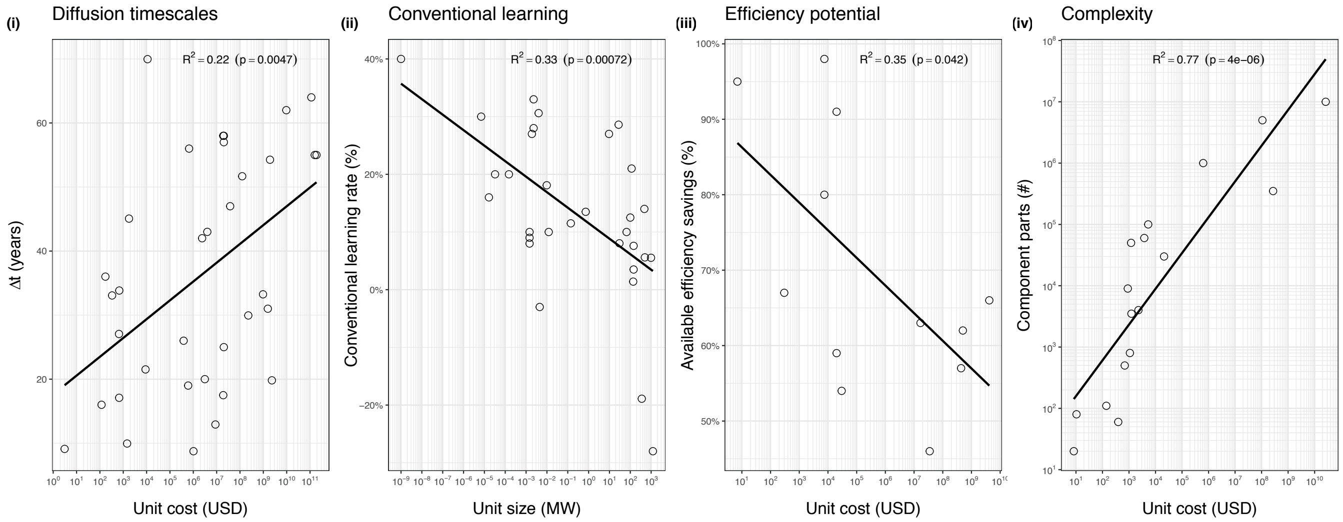


Figure 7. Characteristics of accelerated low-carbon transformation on the granular-lumpy continuum. Data points in each panel represent an energy technology. Unit size and unit cost correlate strongly and are used interchangeably as measures of granularity on log horizontal axes. Vertical axes show measures of rapid technology deployment (panels (i) on diffusion timescale and (ii) on conventional learning) and escaping lock-in (panel (iii) on efficiency potential and (iv) on complexity). Panel (i) Dt, the time period over which a technology diffuses from 1 to 50% market share. Panel (ii) conventional learning rate, % cost reduction per doubling of cumulative capacity, conflates two drivers of cost reduction: unit-scale economies (more capacity per unit) and experience (more units). Descaled "true" learning rate, % cost reduction per doubling of cumulative numbers of units, strips out the effects of unit-scale economies on cost trends. R^2 and p values denoted by asterisks describe simple bivariate model fits (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$). Source: Adapted from Wilson et al. (2020a).

upscaling in unit size. Granular versus lumpy is clearly a continuum, not a binary categorization (Wilson et al. 2020a). Despite these caveats, the illustrations as reflected in the broader literature indicate that granular innovations can be expected to have significantly higher diffusion rates and thus shorter adoption times. Generally, they are also 'closer' to the consumer compared to the upstream lumpy ones where decisions of the consumer do not directly influence adoption but rather only indirectly through their demand for end-use services. Consumers do not purchase power plants, microchip factories, trains, or planes.

More granular innovations can be expected to have faster diffusion, lower investment risk, faster learning, more opportunities to escape lock-in, more equitable access, high job creation, and larger social returns on innovation investment. In combination, these advantages enable rapid change. This is highly relevant for the role of innovations in the context of transformative change. It indicates that for rapid transformation to occur investments should be directed toward innovations with high learning and diffusion potentials.

As such, this is also critically important for the achievement of the Six TWI2050 Transformations from digitalization to decarbonization and health.

Digital Revolution

Digital technologies are examples of innovations with exceedingly rapid diffusion because they are granular, even though they are embedded in large and complex infrastructures and systems. Smartphones, AI, connectivity (the Internet of Things), digitalization of information, additive manufacturing (such as 3D printing), virtual or augmented reality, machine learning, blockchain, robotics, quantum computing, and synthetic biology are all examples of granular innovations. Digital technologies have spread rapidly in much of the world. They can be a powerful influence in helping overcome social inequalities, but they are also characterized by inequalities themselves (TWI2050 2019). Large disparities in access to, usage of, and skills relevant for digital innovations exist, which are summarized as the 'digital divide.' Even more importantly, gaps also exist in the broader development benefits from using digital innovations. Digitalization has often boosted growth, expanded opportunities, and improved service delivery, yet the aggregate impact has fallen short of being inclusive and is thus unevenly distributed. Because of its generally granular nature and fast diffusion and learning rates, the Digital Revolution is already reshaping work, leisure, behavior, education, health, and governance and can facilitate the other five TWI2050 transformations (TWI2050 2019).

Digital technologies and innovations are disrupting production processes in nearly every sector of the economy, from agriculture (precision agriculture), transport (self-driving cars), mining (autonomous vehicles), manufacturing (robotics, 3D printing), retail (e-commerce), finance (e-payments, AI trading strategies), media (social networks), health (AI diagnostics, telemedicine, drug discovery, social distancing apps), education (online learning, virtual classrooms—now becoming mainstream during the COVID-19 lockdowns), and public administration (e-governance, e-voting). In general, these contributions can raise labor, energy, resource, and carbon productivity, lower production costs, expand access to services, and dematerialize production, but they can leave many behind without proper policy frameworks and social 'escape hatches.'

There are also clear dangers and downsides to the Digital Revolution, including the loss of jobs, rising inequality, and the further shift of income from labor to capital. With automation and advances in AI and robotics, many more workers, even those 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 poorer working conditions. The fears about increasing inequalities have given rise to renewed interest in a guaranteed minimum income.

There are several other perceived threats from the Digital Revolution. Digital identities can be stolen, or artificial identities can be created. Proprietary digital information can be stolen 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-commerce, digital advertising, social media, cloud services, etc.). 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 a next generation of sustainability challenges. General purpose AI and other digital technologies will be used in more and more 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 police and army), complementing, substituting, and challenging human-driven decision-making processes. We need to learn to manage and control the next generations of AI, machine learning, and (semi)autonomous technical systems and to align those with our normative settings. Moreover, the digital transformation will redefine our concept of us 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 into what can be called '*Homo digitalis.*' Humanity is moving toward new civilizational thresholds. Super-intelligent machines might even develop a life of their own, with the capacity to harm human agents. Like in humans, machine pandemics and system failures may cause threats to human wellbeing like the great economic depressions in the past.

The digital transformation calls for a comprehensive set of regulatory and normative frameworks, physical infrastructure, and digital systems, to capture the benefits of the Digital Revolution while avoiding the many potential downsides. An essential priority should be to develop STI roadmaps to better understand the potential benefits and dangers of digitalization. The principles of digital transformation for sustainable development have yet to be written.

Decarbonization through innovations

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 systems and reduced carbon intensity (coal has less carbon than biomass per unit energy). Further evolution toward energy-dense oil and gas yet again reduced the carbon intensity of energy. For example, natural gas has half the emissions compared to coal and the power plants are more granular. The pervasive decarbonization continued with the current rapid penetration of renewables, such as wind and photovoltaics, due to their generally granular nature and rapid learning, together with the contributions of lumpy nuclear and large hydropower. Renewables, nuclear, and large hydropower can be characterized as being near-zero emissions systems. Thus, the pathway is clear, although it is not fast enough to offset increases in demand so that in absolute terms emissions are still increasing at historical rates. The granular nature of renewables offers the possibility of continued replacement of fossil fuels; however, there is significant inertia in the system due to the lumpiness of fossil technologies.

However, the major disruption caused by COVID-19 may lead to a major rethinking about the inertia and the benefits of large-scale fossil dependence. As energy demand has plummeted through reduced production and mobility, air and water are cleaner, congestion is reduced, and biodiversity is rebounding with animals appearing in places never seen before (see Chapter 3). It is indeed possible that the advantages of a sustainable future for all will become clearer and more desirable. This would further enhance the chance of zero-carbon, granular innovations.

Furthermore, a shift toward renewables is also a shift toward smaller units, with large potential for learning and price reductions (see Chapter 3). For example, Figure 7 has shown that the costs of photovoltaics have declined by two orders of magnitude, and wind is today often the cleanest and cheapest source of energy. Granularity and decentralization need a higher degree of interconnectedness of the system through 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 efficiency, decarbonization, and digitalization (TWI2050 2019).

More granular technologies offer larger potential efficiency gains, particularly for individual and household users for whom energy input costs have proven less salient than for industrial users of more lumpy technologies (Wilson et al. 2020a). Improving the efficiency of end-use technologies leverages more than proportionate improvements in overall system efficiency. Currently, one unit of energy saved through end-use efficiency avoids the need for 3.2 units of primary energy resource (Wilson et al. 2020a).

Across developing nations, solar, microhydro power generators, hybrid systems (of many components), batteries, and smaller diesel generators are part of a large suite of reliable, cost-effective energy sources that can enable the full suite of energy services—lighting, cooking, heating, and air-conditioning as well as productive services for small, medium, and even large enterprises (NASEM 2019a).

Moreover, it has become increasingly apparent that the provision of modern low emissions energy that is affordable and reliable, is a critical building block for achieving other SDGs, a high quality of life and wellbeing, through improvements in education, health, food production, clean water, sanitation, and increasing resilience to climate change, security, and safety (NASEM 2019a) (Figure 8).

Today's reliable, affordable, and resilient energy options are driving a new paradigm of heterogeneity. Distributed solutions today offer increasingly compelling economics for those without access to traditional energy carriers, suggesting a fundamental reconsideration of infrastructure policies, energy access solutions, and economics that do not rely on uniform—or old and outdated—assumptions of energy systems, and embracing a portfolio of solutions versus singular approaches.

Smaller-scale renewable-based energy systems are becoming increasingly attractive economically, offering rapid scalability and applicability to serve growing energy demands and provide critical services (such as communications, lighting, and water pumping/

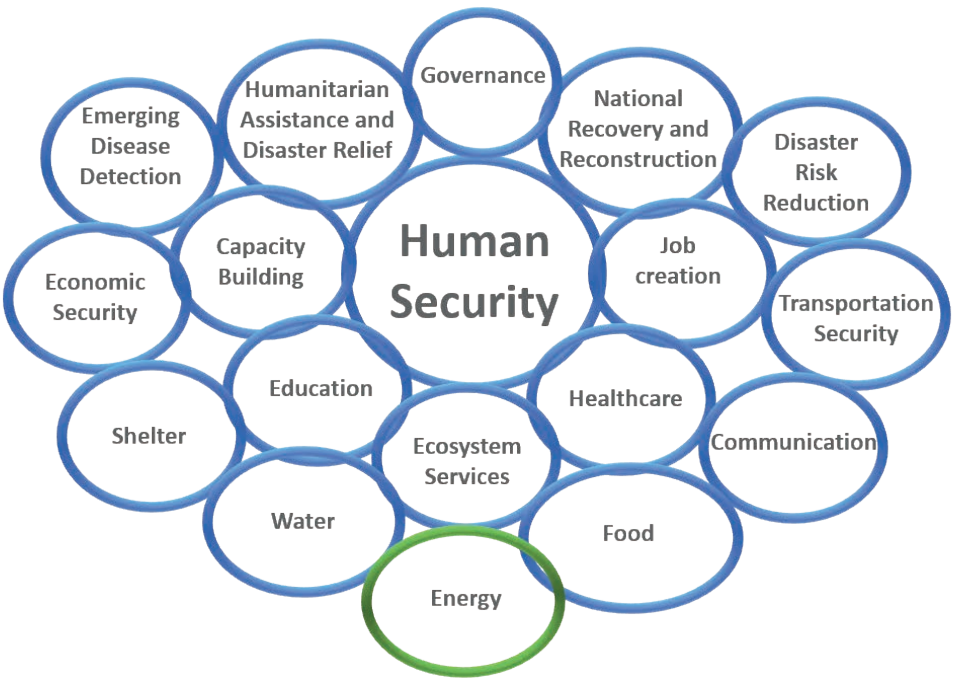


Figure 8. Energy within the building blocks of human security. Source: adapted from Eric Rasmus, Infinitum Humanitarian Systems.

purification—all that enable healthier, productive lives, education, reduced child/women labor, etc.). Utility-scale variable renewable systems offer the potential to substantially reduce local air pollution, drastically cut GHG emissions, and provide reliable energy at low cost. Application of the appropriate mix of these heterogeneous energy systems offer developing countries another opportunity for leapfrogging. Much as cell phones and wireless communications have transformed communications in developing countries, distributed, affordable, and clean energy systems offer a compelling opportunity to leapfrog traditional energy paradigms.

Clean energy solutions, particularly renewable electricity technologies, have expanded globally over the past decade and offer an unprecedented opportunity to enable sustainable energy solutions across the globe (NASEM 2018). In most locations, renewable-based solutions are the most cost competitive option for new power, and in many locations, solutions are hybridized with battery storage to provide additional flexibility and critical services for grid management. Today, renewables supply nearly a third of global electricity capacity (IRENA 2020), with annual capacity additions growing from a few GW nearly a decade ago to over 170GW in 2018. With total installed fossil electricity capacity estimated at ~4.5TW, renewables have an opportunity to replace approximately half that total in the next 10 years (at today's annual installation rates) and possibly greater, implying significant reductions in GHG emissions from the power sector. High renewable-based solutions have been realized in multiple jurisdictions, breaking down myths that represent uninformed barriers to advancement, and lessons can be applied across the globe.

Agriculture through innovations

Agriculture is now a dominant force behind many environmental threats. The development of 'industrialized' agriculture has met the need to feed an increasing population with higher-quality foods, through increases in yields, productivity, and efficiency, and more nutritious crops. The grand challenge of our times is reducing agriculture's environmental harm. A significant reformulation of food production and forestry are necessary if we aim at meeting society's growing food needs while simultaneously keeping human activities within planetary boundaries.

Today's agriculture routinely uses sophisticated technologies such as robots, temperature and moisture sensors, aerial images, information technology, robotic systems, global positioning systems (GPS) technology, and molecular biotechnology. These advances allow businesses to be more productive, efficient, profitable, safer, and more environmentally friendly. Desired benefits include:

- Decreased use of water, fertilizer, and pesticides, which in turn lower food prices
- Higher labor productivity, effectivity, and efficiency
- Higher crop productivity while increasing the efficiency of natural resources use and reducing environmental impact
- Less runoff of chemicals into rivers and groundwater, lower pesticides and herbicides use
- Reduced impact on natural ecosystems, restoration and reforestation of abandoned lands, biodiversity recovery
- Increased worker safety

However, industrial agriculture has created many side effects that still need to be confronted, including excessive deforestation, loss of biodiversity, soil erosion, chemical pollution, direct and indirect contributions to GHGs, and global warming. Today, agriculture should conceptually be understood as a partnership with our biosphere instead of an extraction industry. Vigorous innovation lags or is lacking altogether in areas that are not immediately profitable to the market, mainly in the developed world.

Innovation opportunities for sustainable ocean development

The High-Level Panel for a Sustainable Ocean Economy estimates that innovative ocean solutions can contribute 25% of the desired climate change mitigation (Hoegh-Guldberg et al. 2019) and stresses its importance for human wellbeing and livelihoods providing food, marine genetic resources, energy, minerals, and human health. The global 'ocean economy,' which includes all maritime transport, fishing, offshore oil and gas, and tourism, is projected to double its size to $3 trillion by 2030 (OECD 2016). The majority of the world's megacities (15 of the 23 most populated cities in 2015 (Blackburn et al. 2019)) are situated at the coasts. Greater than average population growth in the coastal zones will lead to more than one billion inhabitants by 2050 (Merkens et al. 2016) supported by rapid coastal development (Sengupta et al. 2018). How will this largest human system interact with the largest physical system on the planet in a sustainable way promoting prosperity and resilience (Mega and Mega 2019)?

Many countries have developed blue growth and innovation strategies, anticipating growth of their ocean portfolio including ocean energy, mineral resource extraction, fisheries and aquaculture, coastal tourism, transport, and marine biotechnology.

To ensure that 'blue innovations' become 'green'—which means sustainable and equitable—and economically and ecologically balanced, integrated, transdisciplinary and cross-sectoral innovation is needed, bringing together natural, social sciences and humanities as well as policymakers, resource managers, private and public sector, and society at large. Sustainable development of ocean use urgently needs coherent and consistent governance across all regions and sectors of human activities interacting with the ocean, particularly for rapidly growing coastal regions. The UN Decade of Ocean Science for Sustainable Development (2021–2030) has set out to connect science, knowledge, and development to build the needed capacity and cooperation around the globe (Pendleton et al. 2020).

Health through innovations

Innovations have always played an important role in health systems. Hygiene and social distancing were recognized early as essential for fighting infection. The advent of antibiotics and modern surgery brought a paradigm shift in health care systems. More recently, 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. This was accompanied by enabling institutional innovations to bring health care to increasingly more people though pervasive medical coverage in many parts of the world.

Digital medicine involves new revolutionary technologies and algorithms, combining the fields of traditional 'Western' medicine, computer science, robotics, and applied mathematics (TWI2050 2019). Recent trends range from new technologies and business models to mobile health, telemedicine, 3D printing, robotic surgery, computer-assisted diagnoses, gene therapy, and virtual reality (for more detail see TWI2050 2019).

Telemedicine has the potential to reduce inequalities in access to modern medicine and medical practitioners experienced in many parts of the world, particularly in remote communities, and will help overcome the shortage of qualified health professionals, reduce travel and waiting times for patients, resulting is large savings for the health system. The use of telemedicine services has increased dramatically during the COVID-19 pandemic with patients discouraged from personal face-to-face visits to general practitioners in an effort to limit the spread of the virus.

In response to surging demand for medical equipment to deal with COVID-19, 3D makerspaces around the world started production of face shields and respiration devices, in close coordination with hospitals and health workers (McCue 2020). Furthermore, several bottom-up hackathons and open innovation challenges[2] have been organized to find digital solutions to ease the pressure in the field calling users, consumers, or individuals or firms with ideas and equipment to collaborate in meeting the demand to combat social challenges. These clearly illustrate the potential of such initiatives, given the spread of digital technologies such as 3D printers and scanners, in addition to information communication technologies (ICT) to diffuse and share the design concepts.

Computer modeling and big data are increasingly used for drug discovery, which taken together with advances in synthetic biology, offers the possibility of not only discovering new drugs and therapies, but also making them personalized and cheap to manufacture. AI is being used extensively in the current quest to rapidly develop a vaccine for COVID-19 and in general for better disease diagnostics and treatment.

Taken together these technologies will have significant impact on the global health system for both patients and providers. Undoubtedly this will lead to better health outcomes and improvements in human wellbeing and quality of life. However, this revolution is not without risk.

A prerequisite of digital medicine is that a patient's health records need to be digitized and 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. The world has recently experienced a multitude of data breaches and, unfortunately, the health care industry was a major target. According to the *Identity Theft Resource Center Data Breach Report 2017*, health care is the second biggest contributing industry with 334 breaches in 2017 (ITRC 2018); the third industry to expose most records was health care; and the health care industry was hit hardest by hacking, skimming, and phishing attacks.

In many cases, patients are now choosing to leave the health care providers that have failed to protect their data or electing not to have their health records digitized. According to Accenture (2015), more than 6 million people are victims of medical identity theft annually. 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 world. The introduction of a contact tracing app for COVID-19 in the Republic of Singapore[3] to help reduce the spread of the virus resulted in less than 20% uptake by the population due to privacy concerns. A minimum 40% uptake was required for it to be useful in reducing the spread (Criddle and Kelion 2020).

As with all digital technologies, the potential for improvements in the health care sector and achievement of SDG3, will depend on global equitable access to these technologies.

2 For example: https://covid19challenge.mit.edu/

3 For readability, only 'Singapore' will be used in the remainder of this report.

It is interesting to note the impact of the current COVID-19 pandemic on the uptake and diffusion of previously limited or niche innovations. The shutdown of economies and implementation of strict personal distancing measures across the world has seen the rapid deployment of online learning for students, telemedicine, remote working and telecommuting through videoconferencing, 3D printing of personal protective equipment, and AI for vaccine development to name just a few. Although global economies are forecast to shrink dramatically as a result of the pandemic it could be argued that the impacts could have been much more significant if these granular technologies were not 'on the shelf ready to go.' It has been suggested that many of these innovations will become the 'new normal' post-COVID-19 (see Box 11). It is unfortunate that it takes a global pandemic to highlight the advantages and efficiency of these innovations.

2.4. Epidemics, pandemics, and innovation

Disease epidemics and pandemics have often had devastating impacts on health, societies, and economies. Although with a very different mortality rate, elements of the COVID-19 pandemic are reflected in pandemics of the plague (black death) throughout history. The bacillus that causes that disease, *Yersinia pestis*, is transmitted by fleas associated with rats. The disease has three forms, of which the bubonic form has a 40%–70% fatality rate and the pneumonic form is generally fatal without treatment. Significant research efforts led to the discovery of the causative bacterium in 1894 (Butler 2014).

There were at least three major pandemics: the Justinian plague around the Mediterranean in the 6th century AD, the black death in Europe in the 14th century, and the epidemic in the Republic of India[4] and China during the middle of the 19th century (Stenseth et al. 2008). In western Europe, about one third of the population died between 1348 and 1350 from the plague (Slack 1989). Mortality of 25% or more of the urban populations was common; for example, 60% of the population of Genoa was likely to have died in 1656–1657. The black death had a major impact on Europe's socioeconomic development, culture, art, religion, science, and politics. There were other major epidemics around the world.

Efforts to control plague pandemics are echoed in the actions being taken to control COVID-19, including travel bans (the pandemic may have started in Asia and then traveled by ship), isolation of cases, contact tracing, mass burials, and proposals for unusual treatments (Slack 1989, Zietz and Dunkelberg 2004, Signoli 2012). The term 'quarantine' is Venetian in origin based on the 40-day travel restrictions imposed in Venice in the 1370s. Recognizing the risks to health professionals, personal protection equipment, including a long cape and complex mask, were designed based on the prevailing miasma theory of disease transmission (Mussap 2019). Other innovations were improvements in living conditions that moved people away from animals into, for example, brick houses that are less hospitable to rats, measures to rat-proof dwellings, and public education about the disease, including publishing regular lists of the numbers and causes of deaths (Greenberg 1997, Zietz and Dunkelberg 2004). In Seville in 1582, the city council imposed plague restrictions that attempted to balance medical concerns with economic interests (Bowers 2007); the restrictions included quarantines and travel bans, along with open lines of communication with residents and individual exemptions to maintain selected economic activities.

The world is deploying significant resources to bring the COVID-19 pandemic under control, including new investments into health systems to increase their resilience to unexpected challenges. While this is certainly needed, the history of population health indicates the sustainability of these investments over time is not assured. One example is the history of the control of yellow fever. Yellow fever is a viral disease primarily transmitted to humans by the mosquito *Aedes aegypti*. Mortality from yellow fever is high; of the 15% of cases that develop severe illness, the case fatality rate is 20%–60% (CDC 2018). There were widespread epidemics of yellow fever starting at least in the 17th century. The geographic range of yellow fever expanded with shipping and commerce (Gubler 2004). At the beginning of the 20th century, construction of the Panama Canal was at a standstill because of the high prevalence of yellow fever (PAHO 2020b). Effective control of *Aedes aegypti* was central to successful completion of the canal. This continued until the last 25 years of the 20th century when there was a resurgence of *Aedes aegypti*. Factors contributing to this resurgence include a failure to maintain vector control programs. It had become increasingly difficult to convince policymakers to support programs to eliminate a mosquito when the numbers of cases of the diseases it carried had declined dramatically. Figure 9 shows the geographic distribution of *Aedes aegypti* in the Americas in 1930, 1970, and 2004 (Gubler 2004). One consequence of this resurgence was an increase in another disease carried by Aedes: dengue fever. In 2019, there were more than 3 million cases of dengue fever in the Americas (PAHO 2020a); this far exceeded the previous largest epidemic in the region when 2.4 million cases were reported in 2015.

4 For readability, only 'India' will be used in the remainder of this report.

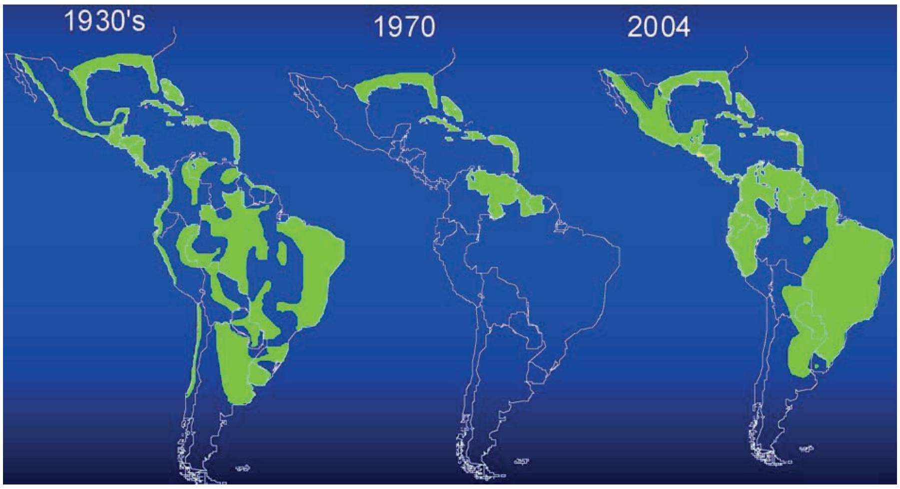


Figure 9. The changing epidemiology of yellow fever and dengue, 1900 to 2003: full circle? Comparative immunology microbiology and infectious diseases. Source: Gubler (2004).

Responses to COVID-19 are furthering traditional public health approaches, from rapid testing kits to new ways to manage pulmonary damage to vaccines. These will interact with other trends; examples include the speed of innovation, use of big data and AI, digitization, and miniaturization. For example, the importance of contact tracing is leading to the use of cell phone data to monitor the movement of individuals—and to discussions on how to balance the need for privacy with the need for information useful to control the pandemic. Figure 10 shows the difference across countries in confirmed cases and COVID-19 deaths.

Investments in health systems, particularly weak systems in low-resource settings, and science-informed decision making and implementation could be intentionally focused on increasing the sustainability and resiliency of these systems in ways that could support achieving transformations to achieve SDG3, which would support achieving the other SDGs and fighting COVID-19 (see Box 4).

2.5. Innovation investment and financing

As the future is inherently unpredictable, and to an extent a function of human intentionality in the Anthropocene, arguably the direction and magnitude of investments will help shape the evolutionary changes in the decades to come. Trillions of dollars have been pledged for economic stimulus to revive economies around the world after the unprecedented and deliberate shutdown in order to overcome the COVID-19 crisis. Sachs (2020) argues that this is a display of "intellectual confusion of the moment by labeling as 'stimulus' the legislation to pay workers and firms during this shutdown period. This is not stimulus, but [needed] income maintenance during a temporary society-wide quarantine." Indeed, the

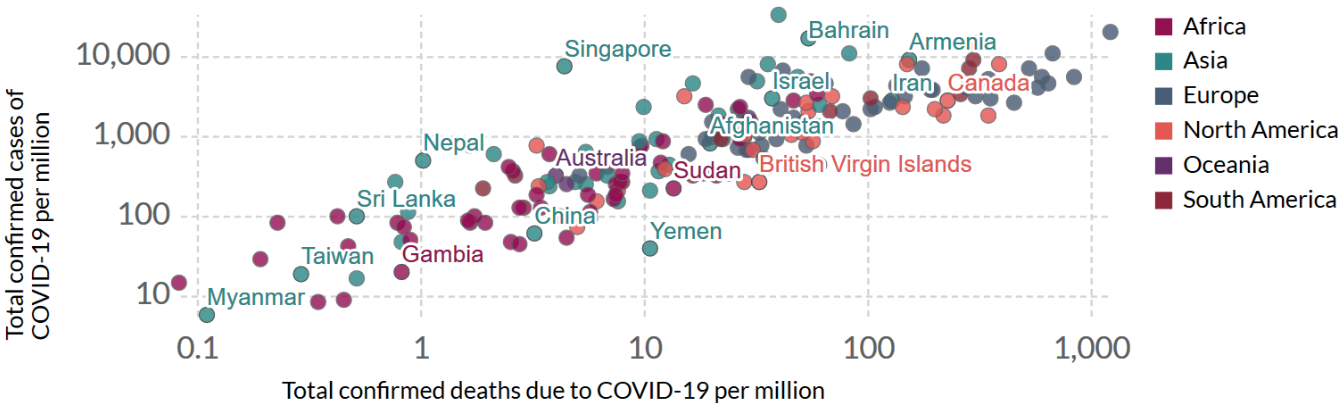


Figure 10. Total confirmed COVID-19 deaths vs cases, 2 July 2020. The number of confirmed cases is lower than the number of total cases. The main reason for this is limited testing. Source: European CDC Situation Update Worldwide graph by OurWorldInData.org/coronavirus CC BY.

Box 4. Digitalization capabilities and COVID-19—social technology and innovation.

The digital capabilities of Taiwan, Province of China,[a)] helped enhance the effectiveness and efficiency of its response systems, and coupled with citizen science and various social initiatives, allowed to develop effective governmental and community strategies to contain the outbreak. It involved three complementary measures: effective distribution of face masks, comprehensive testing, and self-isolation measures.

A Social Distancing App which uses AI and Bluetooth wireless communications protocols was also developed to alert users on their mobile phones if they come too close to one another based on the 1.5 meters indoor and one-meter outdoor proximity guidelines. Privacy is also protected as users are not required to register and data is not stored in the cloud, while a new hashed ID generated every 15 minutes prevents user recognition. Users who choose to upload their data onto the server to assist in contact tracing can do so anonymously, with the data deleted after seven days (Chang 2020).

The wearing of face masks has become a crucial preventive tool against the spread of the COVID-19 virus worldwide. Developing quickly the capability to produce its own masks and a rationing system for their distribution has shown helpful. The digitalization of the National Health Insurance database, and the "the infrastructure upgrades and data management experience accumulated over the years," also enabled the surgical mask rationing database and online system to be quickly set up (Ngerng 2020). The first component for the rationing was the Pharmacloud system that was initiated in 2013 to store medical records in the cloud for health care decentralization. The second was the online g0v community, a decentralized civic tech community that grew out of the Sunflower Movement that started in 2014. It facilitated the growth of open-source communities that use open data and civil technologies to promote participatory governance. Through this, citizens with IT skills and engineers, using National Health Insurance (NHI) data, developed online maps with real-time availability of masks. This resulted in a variety of maps for different target audiences.

Stringent testing protocols were an effective way to contain COVID-19. The Central Epidemic Command Center (CECC), which was activated to coordinate inter-ministerial responses, integrated travel history data from the National Immigration Agency (NIA) with the Pharmacloud system. This allowed doctors to determine if patients with respiratory symptoms and those who traveled abroad should be tested for the coronavirus. The database integration also enabled the back tracing of patient records and travel history for retrospective testing when required.

Self-isolation and home quarantine are another effective line of defense to fight COVID-19, and the CECC tasked Chunghwa Telecom to develop an 'electronic disease prevention platform' where GPS data from mobile phones using the triangulation of base station data could be used to track people's whereabouts, whereby people who leave their homes would receive warning messages which are also sent to the police and health agencies. However, this tracking platform and the integration of medical and travel databases have increased privacy concerns, though the government has claimed that the Communicable Disease Control Act and the Special Act on COVID-19 Prevention, Relief and Restoration gives the CECC the authorization to enforce such disease prevention measures where required.

a) For readability, only 'Taiwan' will be used in the remainder of this report.

post-COVID-19 economic crisis may be as deep and fundamental as the Great Depression a century ago, which sent humanity on a new development pathway that brought the 'Great Acceleration' after the Second World War. Clearly, the solutions of the 1930s are not relevant to meet today's challenges but we argue that humanity is at a crossroads, that there is a window in which we might embark on a just and sustainable future within planetary boundaries, but also a possible retrograde or a return to the 'old normal.'

Innovation toward sustainability is a cumulative transformation that needs to be sustained and 'socially steered.' With appropriate governance, norms, values, and behaviors, it could bring efficiency and sufficiency needed for prosperity and wellbeing for all (see Chapters 3 and 4). Investments are essential for achieving such as sustained and pervasive transformational change.

Total global investment is about 23% of economic output, or about $28 trillion purchasing power parity (PPP) per year. It has varied, with a high of over 25% in the aftermath of the 2008 financial crisis and subsequent economic depression (World Bank 2020). Global R&D investment is estimated at some $2 trillion PPP per year (IRI 2016) or about 10% of total investment or 2% of global economic output.

Figure 11 shows human and financial resources devoted across counties and major word regions toward R&D as an indicator of investments in innovation and a proxy for countries' capacity for transformative change. The size of the circles is proportional to R&D expenditure while the horizonal axis shows R&D share of the GDP and the vertical axis the number of researches per thousand employees. The State of Israel and the Republic of Korea[5] lead by a wide margin on both yardsticks, while China and the USA lead in terms of absolute expenditures. This comparison is a proxy for innovative capacity because these efforts are sustained over time growing gradually from year to year. What is not shown is the distribution or the direction of their expenditures which would be stronger indicators of transformative potential.

5 For readability, 'South Korea' will be used in the remainder of this report.

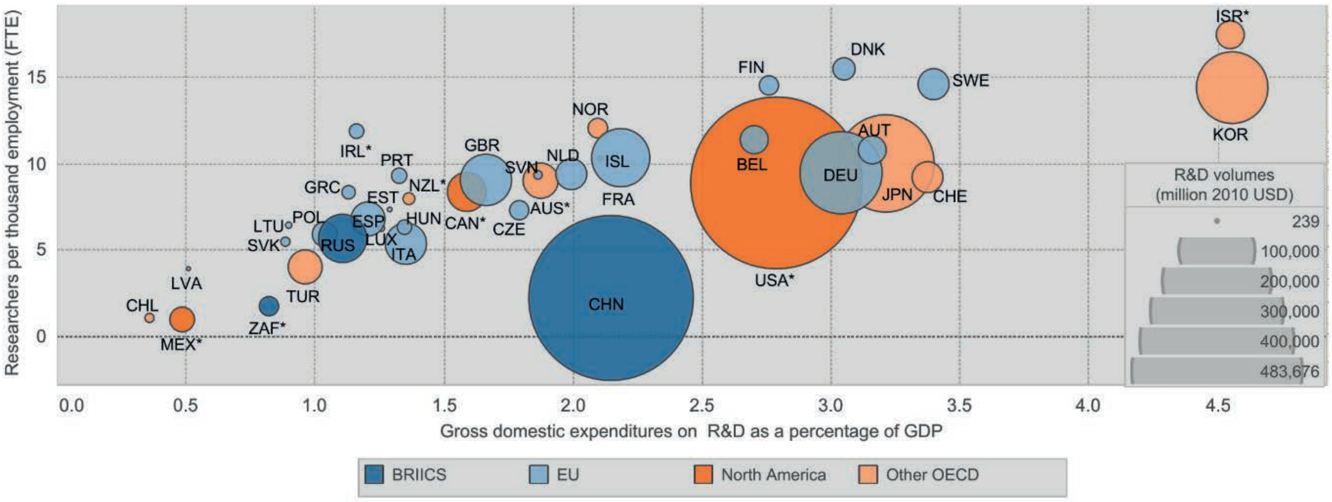


Figure 11. Human and financial resources devoted across counties and major word regions toward R&D, 2017, as an indicator of investments in innovation. The size of the circles is proportional to R&D expenditure while the horizonal axis shows R&D share of the GDP and the vertical axis the number of researches per thousand employees. Source: OECD (2020a).

R&D intensity—gross expenditure on R&D as a percentage of GDP—is one of several indicators used as targets to measure progress toward achieving SDG9 on innovation and is also an indicator of STI's capacity to fulfill the Six Transformations. Growth in R&D intensity was widespread across the majority of OECD countries in 2018, with the USA, Japan, Germany, and South Korea accounting for much of the increase. In some countries, such as Canada and the Kingdom of Sweden, R&D expenditure remained stagnant (OECD 2020a).

An important development, according to the OECD STI database, is that in terms of PPP and recent trends, China may already account for the largest volume of R&D expenditure in the world (OECD 2020a). Yet when comparing economies based on exchange rate conversions to a common currency, there is still a very significant gap between China and the USA, with R&D expenditure in the former only 50% of the latter. Other OECD indicators complement this comparison. In 2018, the USA had 23% more top-cited publications (top 10% of cited publications within a given field) than China, despite having a lower number of indexed publications. Selected OECD Patent Statistics indicate that China overtook Japan in 2017 for the second most patent applications, behind the USA. Based on recent trends, China's patent applications may have surpassed the USA in 2019, or even as early as 2018.

All of these indicators are 'input' measures of expenditure in STI, patent applications, and publications and as such are extremely relevant for assessing innovative capacities, but they are only proxies as they do not measure the 'output,' namely knowledge creation and innovative activities. Learning curves are another way of assessing progress of innovation but these are limited to certain measurable examples and do not give a holistic systems view for whole economies or the world.

Equally important for assessing innovation is the direction and structure of expenditures and activities. Generally, the private sector continues to be the main global driver of R&D efforts and investments in general. The private sector accounts for 71% of all R&D performance in the OECD and saw its R&D expenditure increase by 4.2% in 2018. R&D investment in the higher education sector grew by 2.3%, while those by governments rose by 4.0%—the highest rate since 2009. Yet, R&D performance among government institutions remains only 13% higher than it was before the onset of the global financial crisis—on par with 2010 levels—and accounts for less than 10% of OECD R&D expenditure (OECD 2020b).

An important principle is the subsidiarity that holds that social, political, and economic issues should be dealt with at the most immediate level that is consistent with their resolution. In the case of investments, this would involve the private sector consisting primarily of businesses, but also NGOs and foundations in the case of R&D. Yet, economic theory shows that the private sector generally underinvests in fundamental R&D and even more chronically in public goods such a health care, education, infrastructure, and social expenditures, because of difficulties of appropriating any gains achieved. The private sector is driven by profits realized in markets and not necessarily by social and public good, although there are increasing numbers of enterprises that include such considerations in their investment and R&D decisions. Hence there are some salient reasons why increasing government expenditures and support of transformative change are called for.

In fact, government expenditure for R&D overall should grow substantially in 2020 in the aftermath of 'stimulus' expenditures in response to the COVID-19 pandemic and economic recovery in its aftermath. Chapter 4 estimates the total government stimulus commitments at approximately $7 trillion—a figure that is close to three times the size of the estimates of the $2.5 trillion funding gap per year for achieving the SDGs and the Six Transformations calculated prior to the onset of the COVID-19 pandemic.

As mentioned, R&D intensity and other R&D indicators are useful as proxies for progress toward achieving SDG9. However, the 2030 Agenda is holistic, requiring a broader perspective to assess the full contribution of STI to the SDGs and the Six Transformations. Public funding of R&D is often needed to support the development of radically new solutions that help attain more than one objective at once and create multiple co-benefits (TWI2050 2018, OECD 2020b). R&D budget data do not have the granularity of some SDGs. STI efforts can ultimately affect several SDGs at once—especially in the case of basic research—but the channels by which this happens can take several years to materialize into concrete solutions and will likely require additional investments (OECD 2020b).

Figure 12 presents tentative, experimental mapping of OECD government R&D support onto four SDG clusters. This clustering treats government support for the general advancement of knowledge and R&D tax incentives as related to STI for SDGs. Support for industry and knowledge has been the fastest growing category since consistent records have been available. More recently, growth in R&D funding has focused on defense spending, which is identified here with the SDG on security. Funding directed toward health and society reached a peak in 2009, while there has been limited growth in support for R&D on planet and infrastructure SDGs (OECD 2020a). Hopefully, there will be an increase of funding in these critical areas in the future. Chapter 3 gives estimates for investment needs to achieve SDG targets related to basic human needs. COVID-19 has created a window of opportunity to allocate stimulus funds toward sustainability transformations and policies promoting efficiency, sufficiency, and innovation. Whether financial resources are distributed for more sustainable purposes is not guaranteed; however, this will depend on policy and political reforms discussed in Chapter 4.

2.6. Science, technology, and innovation for sustainable development

Sience, Technology and Innovation (STI) are at the core of human development. They have greatly contributed to the explosive development since the onset of the Industrial Revolution such as the doubling of life expectancy, secondary education for half of humanity, and wellbeing for billions. However, they have also brought about negative impacts on the environment and society. While all negative externalities and impacts cannot be anticipated, STI can and should focus on supporting the achievement of the SDGs. In particular, public STI policy needs to internalize this overarching goal for enabling and achieving the 2030 Agenda.

Since the UN member states agreed the SDGs in 2015, STI has been expected to play a major role to address these goals and targets, but for that to happen

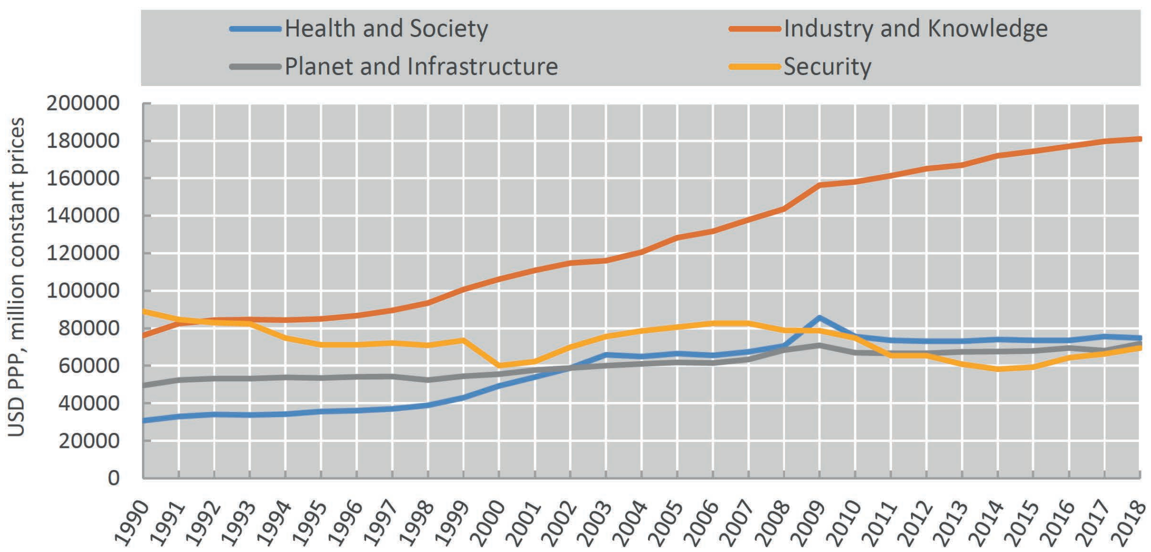


Figure 12. Estimate of total government support for R&D in the OECD countries by SDG-related categories, 1990–2018. It indicates the largest increase in industry and knowledge followed by health and society with a slight increase for planet and infrastructure and a slight decline for security which includes defense. Source: OECD (2020a).

traditional values and methodologies of STI need to be redesigned and transformed.

Various agencies, including the UN Interagency Task Team on STI for the SDGs (UN-IATT), the UN-science advisory committee, IIASA, OECD, EU, and Japan have been developing, analyzing, and proposing new thoughts, frameworks, and methodologies to redesign the STI ecosystem for innovation, efficiency, and sufficiency for achievement of SDGs; such as the Guidebook of STI for SDGs Roadmaps, GSDR2019, TWI2050 , Mission-oriented policy analysis, and EU Smart Specialisation Strategies and Society 5.0.

Based on these proposed frameworks, it is time for us to put into practice the ways and means of implementing pathways to achieving the SDGs goals at global, regional, national, and subnational levels (TWI2050 2018). The global STI community is now under great pressure to transform modern science and technology, its policies and systems that have been built over the past 200 years.

Research systems and organizations based on traditional social and industrial structures, lifestyles, culture, and science and technology areas need to be redesigned for the age of SDGs and beyond; from agenda setting processes, funding, and evaluation systems, to human resource development methods and career paths. It is necessary to diversify R&D investment and priorities according to actual needs and context. Collaboration between natural sciences, humanities, and social sciences is essential. Cooperation between supply and demand sides and combination of top-down and bottom-up approaches is important.

We need to accumulate, share, and feed back those efforts for reflection and transformation. It is necessary in parallel to recognize the importance of preserving basic science, and dialogue between policymakers and researchers. Building trust and keeping scientific quality, integrity, and code of conduct is also important.

However, initiating transformation is difficult due to institutional inertia by incumbent actors with vested interests and consumers/users with habits of following routines. In addition, the globalization of economic and social activities that has occurred over past decades has created intricate webs of activities, making transformation a complex process. Furthermore, existing studies indicate that current policy instruments are either absent or ineffective for achieving the magnitude of transformation needed in the expected timeframe (Weber and Rohracher 2012, Kivimaa and Kern 2016, Kern et al. 2017). This means that unless there are substantially advantageous (simple, low cost, superior, and universal) alternatives offered to individuals, achieving change is going to be difficult (Steward 2012).

How STI can inform policymaking about SDG interlinkages

The 2030 Agenda is unique in that the implementation should adhere to principles of indivisibility and universality. Yet, the 2030 Agenda does not specify what characterizes its indivisible nature, which interactions exist between the SDGs, the nature of these interactions, or what they imply for policy and decision making. Neither does it provide guidance on how to identify or address potential spillover effects and cross-scale interactions. The fast-emerging field of what could be referred to as SDG interaction studies seeks to provide such guidance.

Through such studies, the scientific community could play a vital role in supporting evidence-based decision making, for example by strengthening the knowledge base on SDG interactions and integrated policymaking. Indeed, since the adoption of the 2030 Agenda, the number of studies aiming to create an integrated understanding of the SDGs has been growing rapidly. However, as yet there is no general agreement on what it means to take an integrated approach to the SDGs, nor on how to respond to the principle of treating the 2030 Agenda as an indivisible whole.

In a recent review by Bennich et al. (2020)[6] of the literature on SDG interactions the following four key questions were asked:

- What policy challenges related to SDG interactions have the scientific community addressed?
- How are SDG interactions conceptualized?
- What sources of data are used to underpin the interactions?
- What methods have been used to identify and analyze SDG interactions?

The answers to these questions form four themes along which current SDG interaction research can be mapped:

Policy challenges. Most research hitherto has at least had an implicit objective to strengthen policy coherence, assuming that integrated and more coherent policies hold the potential to optimize resource use and generate sustainable outcomes. Some studies focus explicitly on institutional barriers for policy coherence on how to better capture synergies and trade-offs in policymaking. Another example of a policy challenge addressed by the literature is the need for policy innovation, where research typically questions the outputs that traditional policymaking generates.

6 The paper is based on an extensive review including 83 peer-reviewed papers. Bibliometric methods and network analysis tools are used to explore patterns and links between themes. Gray literature has been reviewed as a complement, to deepen the understanding of emerging approaches to support SDG implementation.

Interaction conceptualization. There are numerous ways in which SDG interactions have been conceptualized in the literature. A relatively large group of studies focus primarily on the goals, targets, or indicators constituting the core of the 2030 Agenda. However, a number of studies have linked the components of the 2030 Agenda to specific policy measures or broader themes of relevance in a particular context. Examples include studies exploring the potential impact of a policy on a specific SDG (target/indicator) or studies exploring links between parallel policy agendas such as the bio-based economy and the SDGs.

Data sources. The most common source of data for SDG interaction studies are scientific literature, or gray literature, such as reports, policy documents, and news articles. The second most common source of data is official databases, compiled by international organization (e.g., the UN) or national, regional, or local offices.

Methods of analysis. The methodological approaches employed in the SDG interaction literature span a wide range from qualitative (e.g., scenario building), via semi-quantitative (e.g., cross-impact analysis) to quantitative methods (e.g., General Equilibrium, Integrated Assessment and system dynamics models).

Relatively few frameworks for analyzing SDG interactions have been used in real policy processes. The SDG Synergies approach developed by researchers at Stockholm Environment Institute has already been tested in partnership with national governments and international agencies and is constantly being improved and adapted, with tailored decision-support tools created in the process. Examples of case studies include the governments of the Republic of Colombia, Mongolia, and the Democratic Socialist Republic of Sri Lanka, as well as subnational applications in Colombia and by the European Environment Agency. The approach can be used to prioritize action on SDG targets and to identify the most effective partnerships and collaborations, based on an understanding of real-world interactions between targets in a given context.

The core of the approach is a three-step process of collaborative analysis. The process can involve scientific experts, representatives of different sectors of government, and a range of other stakeholders.

Customization. Every use of SDG Synergies is necessarily unique, depending on the coalition of actors using it, and the context in terms of natural resources, economic conditions, governance set-ups, technological options available, current policies and practices, and prevailing ideologies. These factors, in turn, shape which targets are perceived as most relevant and important by decision makers.

Scoring interactions. The subset of targets that has been selected are entered in a ‘cross-impact matrix,’ and each interaction is given a score against a guiding question. When the objective is to support priority-setting and collaboration, a typical question would be, “If progress is made toward Target A, how does this influence progress toward Target B?” Consistent scoring is facilitated by the use of a scale of different types or strengths of interaction. Two scales have been used: one proposed by Weimer-Jehle (2006), which goes from "strongly promoting" to "strongly restricting," and one by the International Council for Science, which goes from "indivisible" to “cancelling” (Nilsson et al. 2016).

Analysis: beyond direct interactions. With a completed cross-impact matrix it is possible to go beyond the direct interactions and identify patterns, clusters of interacting targets, and other network effects. More sophisticated network analysis methods can be used to gain a better understanding of how progress toward different targets could affect the whole system.

This is an approach that aims at balancing the requirements of policymakers’ realities and scientific rigor that are needed to make the connection between science and policy credible, relevant, and legitimate. The process and all analytical steps are fully transparent and easy to follow by all actors engaged in the process.

Another framework for analyzing SDG interactions for policy planning is the Integrated Sustainable Development Goals (iSDG) model developed by the Millennium Institute (Collste et al. 2017, Allen et al. 2019). iSDG incorporates quantitative analysis and simulations of anticipated future development. The approach thereby offers both qualitative and quantitative analyses of SDG interlinkages on an indicator level. It is a policy simulation tool designed to help policymakers and other stakeholders make sense of the complex web of interconnections between the SDGs. Different to databases and indexes that provide a measure of where a country stands, iSDG focuses on the dynamic interactions within the SDG system to reveal the best paths and progression toward delivering on the SDGs. Different policy choices give rise to different anticipated futures. iSDG also allows for quantifying estimates of synergies between policy options as well as SDGs (see Pedercini et al. (2019)). iSDG has been tested in partnerships with national governments and international agencies. Examples of case studies include the Commonwealth of Australia, China, the Republic of Côte d'Ivoire, the Republic of Malawi, and the Federal Republic of Nigeria[7].

7 For readability, only ‘Nigeria’ will be used in the remainder of this report.

2.7. Regional and national STI approaches to sustainability

Europe

The EU's Smart Specialisation Strategy (S3)[8] is a place-based and innovation-led agenda for socioeconomic transformation, growth, and sustainability. It combines science, technology, and entrepreneurial advances, such as research and development, with territorial development through innovative initiatives. The Smart Specialisation approach looks at territories through a systemic lens, with the assumption that different subsystems and actors have to interact and create synergies in order to generate change. Though originally focused more on economic development and innovation, with the change of the EU's priorities (such as European Green Deal), the Smart Specialisation methodology is being adapted to include sustainability principles and social and environmental aspects from design to implementation. The main objective of the Smart Specialisation approach is to identify and support interdisciplinary innovations with the highest potential impacts. Examples are many and include territorial policy mixes designed to answer specific challenges affecting local communities. They can include policies that nurture talent, creativity, knowledge creation, and diffusion of new ideas and activities; supporting entrepreneurial ecosystems and innovation; the internationalization of universities etc.; enhancing university-business collaborative research; leveraging and engaging scientific and business diaspora; and promoting (horizontal) coordination of administrative processes. There are over 120 Smart Specialisation Strategies being implemented in the EU and worldwide, with the total public investment of over 68 billion Euro in the period 2014–2020. This policy will be continued in the EU until 2027. At the same time, Smart Specialisation is getting more and more attention worldwide, and its uptake is steadily increasing. One of the unique features of the Smart Specialisation process is that the priorities for public-private investment in research and innovation are identified through a wide, inclusive, bottom-up participative process. Thus, the process allows numerous stakeholders from business, academia, and civic society achieve collaborative learning and knowledge-based consensus on future development trajectories. This creates an opportunity for the modification of behavior of actors in territorial systems and increased probability of wider change in socioeconomic and sustainability terms. Interestingly, a wide number of priorities identified in the present generation of Smart Specialisation strategies already focus on sustainable development. They include topics such as: the bioeconomy, climate change, eco-innovations, resource efficiency, smart, green, and integrated transport systems, sustainable agriculture, sustainable land and water use, sustainable production, and consumption or waste management. These priorities are translated into transformative actions mobilizing research and innovation for specific territorial realities and contexts. S3 is implemented by the European Commission (EC), with the support of the Smart Specialisation Platform established at the EC's Joint Research Centre.

The European Green Deal (2021–2027)[9] will be key in fulfilling the shift to a low-carbon, circular economy and the achievement of SDGs. This will require unprecedented integration of policies and measures from local and regional to the EU level and perhaps extending beyond to international cooperation. In particular, the integration and coordination of S3 and STI for achieving the SDGs offers a huge opportunity for social steering of development processes in the EU toward fulfilling the commitments of the Paris Agreement on climate change and the 2030 Agenda. For this, S3 policies at the level of European subnational territories, Member States and non-EU countries need to be aligned with other sector-specific policies and internationally to bring expected sustainability transformation. In the case of S3 policy, for example, this translates to a stronger focus on innovation, support to small businesses, entrepreneurial innovation, accelerators, digital technologies, and industrial modernization toward deep decarbonization of the economy and environmental protection. S3 could expand the boundaries of its current scope and scale while at the same time refocusing its mission by highlighting sustainability: S3 as a 'bottom-up' driver for STI and sustainable development at the subnational level to complement the 'top-down' policies and measures to achieve SDGs at the national and EU levels.

The coordination and integration of S3 and STI development for SDGs require harmonized roadmaps and action plans that meet the challenge of immediate action for long-term goals and achieving synergies across local, regional, national, and EU levels. Overall, this calls for holistic, systemic, and diverse approaches to bring about transformative change. There is no one size or one way that fits all, as reflected in the S3 approach and the SDGs, which outline aspirational but achievable objectives.

Transdisciplinary research project by the OECD

The transdisciplinary research project (TDR) by the OECD Global Science Forum (GSF)[10] focuses on a systematic analysis, methods, and practices across different communities and countries. It aims to

8 https://ec.europa.eu/jrc/en/research-topic/smart-specialisation

9 https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

10 https://www.oecd.org/sti/inno/global-science-forum.htm

promote mutual learning between countries through identification of common barriers and sharing of good practices by:

- Reviewing the theoretical foundations and methods of TDR and differentiating it from other related modes of research and broader policy concepts
- Developing a standardized analytical framework to explore the key variables and determinants of successful TDR
- Using the framework to analyze case studies of specific initiatives
- Analyzing relevant information on national policy initiatives to identify good practices
- Formulating policy recommendations to promote TDR to address complex societal challenges.

To achieve these goals, an international Expert Group from 11 countries was established to oversee and implement the project activities and outputs, building on existing work and engaging with relevant stakeholders. The forthcoming project report (OECD, Zinsstag and Arimoto) consists of two parts (a) the overall study analysis, findings, and recommendations and (b) the collection of 28 vignettes for individual case studies. Each case study is different and the collection as a whole illustrates the diversity of issues; food, environment, urban planning, mobility, health, energy, water, disaster, that TDR can be used to address, and provides some important insights into the practical challenges of bringing together different disciplines and stakeholders to address specific challenges at local, regional, national, and global levels.

The major recommendations in the report pertain to governments, research funders, universities, academic communities, and science associations. Governments should facilitate the engagement of public sector actors (e.g., sharing the relevant public sector data) and incentivize the private sector to participate in TDR. Research funders should provide long-term support, establish centers of expertise and national networks, implement proactive management and monitoring of TDR, emphasize the evaluation of societal as well as scientific outputs and impacts, and support capacity building and participation of non-academic stakeholders.

Universities should develop sustainable institutional structures and mechanisms, cross-department committees and meetings, build long-term relations with stakeholder communities nationally and internationally, introduce TDR learning modules into science education and postgraduate training courses, and support early career researchers who engage in TDR projects.

The academic community and science associations should support innovative peer review and evaluation processes which would promote TDR, support early career researchers who wish to engage in TDR, and contribute to the development of new STI indicators and measures that value multiple research outputs.

An important conclusion is that COVID-19 is a prime example of the need for TDR that effectively brings together science and practice at a local, national, regional, and global level. Participatory stakeholder processes that engage natural- and social sciences and that use academic and non-academic knowledge to address how disease control can be effective while maintaining economic activity and social peace, can guide how societal life and economic activity can best start again after COVID-19 (OECD 2020c).

East Asia

Although many East Asian industrialized countries have developed technology and innovation plans for sustainable development, the impact has been minimal to date. For example, the Taiwan Province of China, [11] Science and Technology Roadmap focuses on 'sustainability and environment' as one of the four pillars for future science and technology policy and long-term emission reduction targets; however, the technological developments proposed by the government were not linked to the SDGs (MOST 2017). In South Korea, the *5th Science and Technology Foresight* was published by the Korea Institute of Science and Technology Evaluation and Planning (KISTEP) to support the formulation of the 4th Master Plan for Science and Technology; although highlighting the importance of several low-carbon technologies, such as using hydrogen reduction for steel production, and wireless charging for electric vehicles, there was no discussion pertaining to the linkage between the development of key future technologies with the SDGs (MSIT and KISTEP, 2017). In 2019, Japan formulated a long-term low GHG emission development strategy, with the aim of achieving climate neutrality by the second half of the century (NISTEP 2019).

In Taiwan the Action Plan to Promote Social Innovation proposed by the Ministry of Economic Affairs in 2018, points out that the SDGs should be viewed as the guiding principle for social innovation. Furthermore, the Action Plan establishes a mechanism to encourage public procurement of social innovation products based on the SDGs. Moreover, the official Social Innovation Database also uses the SDGs as an essential attribute of organizations looking to join the platform and seek funding opportunities. These practices exhibit a close linkage between social innovation and the SDGs, which could enhance public awareness since the abstract goals and targets become the product and service of daily life.

11 For readability, only 'Taiwan' will be used in the remainder of this report.

Box 5. Taiwan, Province of China, 2050 Foresight Project.

The emergence and diffusion of digital innovations including the internet of things (IoT), artificial intelligence (AI), 3D printing (sometimes called additive manufacturing), and green energy technology should be carefully examined through integrative dialogue to include the social and environmental concerns and establish public legitimacy and 'social embeddedness.' The *Taiwan in 2050 (TW2050): Developing a Foresight System for a Sustainability Transition*, a four-year research project funded by the Ministry of Science and Technology, was established to develop a long-term strategy for the sustainable future to 2050, with a specific focus on the impact of digitalization on society.

This multidisciplinary research project organizes experts from futurology, sociology, economic sociology, environmental system analysis, demography, and public health to develop an innovative foresight study to support the sustainability transformation. Initially, the research will undertake horizon scanning, to identify the competitive niche and systemic risk of the technology and society and to have a comprehensive overview of the needed baseline information. Secondly, it will analyze the aging challenge through integrated perspectives, such as the effect on productivity and public health. Thirdly, the relations of social, economic, and environmental factors will be quantified using the Taiwan 2050 Foresight System Dynamics Model, to provide concrete information for scenario planning. Finally, to shape the social consensus of the future roadmap, the participatory approach will be adapted to enhance the social trust toward a long-term vision.

As for the horizon scanning, this study applied the dynamic argumentative Delphi method and in-depth interviews with about 220 experts to identify the critical signals for the technological and societal change. Based on the survey, the key research and innovation issues were identified which included digital transformation in the manufacturing sector, new types of employment resulting from digitalization, the upgrade of electricity grids, and health care reform. Furthermore, the key issues that required extensive social dialogue were also characterized which included the digital tax, autonomous vehicles, PV deployment policy etc. Moreover, the research and innovation topics were further examined through the perspectives of systemic risk and key SDG transformations to enhance the social embeddedness. The five systemic risks were prioritized and included extreme weather events, population aging and decline, social inequality, energy and resource security, and lagged adjustments of industrial structure. As a result, this project developed a nexus map between key research, development and innovation niches, SDG transformations, and systemic risk to guide future research and innovation policies. For example, in order to mitigate the risk of energy and resource insecurity, a move toward a digital and circular economy is needed, and it should be supported by AI-based circular design tools to help the small and medium enterprises (SMEs) to increase their material efficiency.

To accelerate the development of AI, Academia Sinica launched the AI Academy to nurture generations of AI talent for business, especially for small and medium enterprises (SMEs). However, the existing course design focuses on the theory of machine learning and deep learning, and related applications, whereas the ethical, legal, and social issues of AI are not included. Hence, the project team will work to overcome those gaps through the cooperation with the AI Academy to create the synergy between digitalization and sustainability transition.

East Asian countries developed their technological strength through significant investments in science and technology that was helped by government policies to support the licensing, refining, and disseminating of foreign technology, and the provision of quality education, infrastructure, and R&D funding. East Asian countries therefore could serve as a development model for developing countries (e.g., electric vehicle production cooperation under the New Southbound Policy (Fuller 2002, Dahl and Lopez-Claros 2005, Sturgeon and Lee 2015)).

East Asia's practice of responsible consumption and production (SDG12) coupled with its digital capabilities presents an opportunity to develop an alternative pathway toward sustainability (see Box 5), given the right policy mixes. The digital capabilities that East Asian industrialized countries have built have also strengthened their capabilities to cope with the recent COVID-19 coronavirus pandemic (see Box 4).

2.8. Summary

This chapter has elucidated the current state of knowledge on invention and innovation, with an emphasis on the processes and prerequisites, such as granularity and learning, for the widespread diffusion of new technologies. Also highlighted is that although innovation has driven human development, and will continue to do so, it does not come without risk and unintended consequences. The real question is how to harness, or steer, future innovation toward a sustainable future while avoiding further detrimental social and environmental impacts. The chapter provides examples of how STI is already helping to shape a more sustainable future and outlines some regional and national approaches in this area. The following chapter will provide more detail on the types of innovations required to facilitate the Six Transformations, with an emphasis on efficiency and sufficiency, and how these can be deployed at the necessary scale.

The best way to predict the future is to create it.
Alan Kay (born 1940)

3 Efficiency and sufficiency for human wellbeing

3.1. Introduction

The 17 SDGs and the six overarching transformations proposed by TWI2050 (TWI2050 2018) are co-dependent and co-contingent in multiple ways and are from a holistic development perspective indivisible. Yet, some SDGs serve as a better entry point to address all the SDGs in a holistic manner compared to others. The central argument of this chapter is that SDG12 (responsible production and consumption), and in particular its consumption component, serve as an ideal entry point to address the 16 other SDGs. This is recognized by TWI2050, which has adopted SDG12, as one of the Six Transformations that are required to achieve all SDGs. Transforming currently unsustainable consumption and production systems is therefore also key for the other five TWI2050 transformations.

Another key tenet of this chapter is that 'consumption' is not defined in economic terms (commercial goods and services) but from the perspective of human wellbeing and that of services and service-provisioning systems. 'Consumption' in this chapter refers to the services (nutrition, communication, health care, shelter, mobility, etc.) that the use of economic goods and natural resources enable to further human sustenance and wellbeing (see Section 3.2), irrespective of whether they are provided by the formal or informal economy, the public sector, or by households. Service-provisioning systems are (alternative) combinations of infrastructures, products, devices (technologies), and forms of (market) organization that provide particular services. The service concept is well established in some sectors like education or health care, but less so in sectors such as transport or consumer goods where often the misleading idea that commercial product equals wellbeing (e.g., for passenger cars) is advertised by industry. It is therefore important to differentiate services that directly link to human wellbeing (shelter, nutrition, thermal comfort, education, health care, etc.) from those services that are themselves intermediary (e.g., infrastructure construction and operations like roads, schools, or hospitals, manufacturing of pharmaceuticals, construction materials, or consumer goods, goods transport), that is, are required 'upstream' in the form of materials, resources, and infrastructure for the provision of direct wellbeing enhancing services.

Service-provisioning systems are malleable, and a service—as opposed to a product or commodity—perspective offers new opportunities for step changes through innovation and new behaviors in efficiency improvements not apparent from traditional economic analysis. As such, new forms and improved models of service provision underpin the transformations that are at the core of SDG12 with the objective to improve the equitable access to services, while minimizing resource use and environmental impacts.

The discussion on what human development entails involves values and moral judgments. Two main strands that have been prevalent in the discussion on human development are the needs approach and the capabilities approach (Holden et al. 2017). Doyal and Gough (1984) refer to needs as universal and objective goals. In the perspective of the needs approach advocated for by the economist Manfred Max-Neef (1992) (referred to as human-scale development), services are useful if they provide the satisfaction of human needs. While needs are finite and classifiable, how they are met is context-dependent (Max-Neef 1992) and malleable, as reflected in the concept of transformation of service-provisioning systems below. Quantitative frameworks related to the needs approach are discussed in more detail below when discussing access to basic services and Decent Standards of Living concepts. Conversely, the capabilities approach advocated for by, among others, Amartya Sen and Martha Nussbaum, suggests that the objective is to create capabilities—referred to as the capability to reach outcomes that people value and have reasons to value (Sen 2001, Nussbaum 2011). However, in assessing whether capabilities are met, one typically has to refer to some metric to measure if human needs are met (Brock 2009). In the context of transforming useful services for the SDGs some metrics are provided by the SDGs themselves, for example, SDG2 Zero Hunger indicator 2.1.1 on prevalence of undernourishment, SDG3 Good Health indictor 3.2.1. on under-five mortality rate, or SDG6 Safe Water indicator 6.1.1. on the proportion of population using safely managed drinking water services. Others, for example, the capability to engage and communicate with others in society need to be considered in the context of other frameworks where they are explicitly dealt with (e.g., Decent Standards of Living).

Why needs are not universally met and capabilities insufficiently developed today is testified in existing multidimensional inequalities (UNDP 2019, Zimm 2019) encompassing health, relationships, safety, ability to have influence, knowledge, and many other dimensions including financial security. These inequalities cause a lack of social-ecological resilience and subsequently greater risk and exposure to external shocks by those with limited resources (Leach et al. 2018). This is clearly apparent in the current COVID-19 pandemic which over proportionally endangers people living in slums without conditions for social distancing, living with limited sanitation and health care facilities, especially in—but not limited to—the Global South (see Box 7).

Transforming service-provisioning systems is about safeguarding human needs and sharing available resources fairly within planetary boundaries. In this chapter we discuss, through the lens of service provisioning, which types of technological and social innovations could contribute to decrease such inequalities, increasing our collective ability to deal with crises, while also decreasing the pressures on natural resources.

The relationship between the types and levels of services and human wellbeing is highly varied and also highly nonlinear. Figure 13 presents a stylized relationship, whose exact shape will vary by service type and indicator of wellbeing considered, but is presented here for a basic categorization of service levels considered in the following discussion (Section 3.2).

The essential first step in service provisioning is to overcome deprivation. Undernourishment, lack of access to safe drinking water and sanitation, or basic health care services are examples of inadequate or absent service provisioning that affect human wellbeing negatively. Assuring basic access to services (see Section 3.2.2) is thus the first and most important step and entails the highest positive gains in human wellbeing.

Although the provision of access to basic services is essential for survival, it does not necessarily allow full participation in economic activities, society, and higher degrees of self-fulfillment. Rao and Min (2018) developed a quantitative framework of the material resource prerequisites for human wellbeing which are framed through a bundle of services that together provide for so-called 'decent living standards' (DLS, see Section 3.2.3). Associated increases in wellbeing from moving from basic access to DLS remain high. It has been demonstrated that the service levels postulated by DLS can be provided for every inhabitant of the planet largely with existing practices (but with a focus on efficient ways of service provision) while staying well within planetary boundaries (Grubler et al. 2018).

Beyond DLS is a level of service provision that we have labeled here as 'sufficiency' level (see Section 3.2.4 below). Here there are diminishing returns of achieving yet higher levels of service provision and consumption on furthering human wellbeing, but they remain positive. Sufficiency levels are difficult to define ex ante and analytically as they are subject to values and expectations that vary widely across individuals, social groups, and cultures. Yet, there are two important social and environmental constraints that influence sufficiency levels: Pareto efficiency (improvements in service consumption of one individual must not diminish anybody else's consumption) as well as Planetary Boundaries (Rockström et al. 2009). With significant

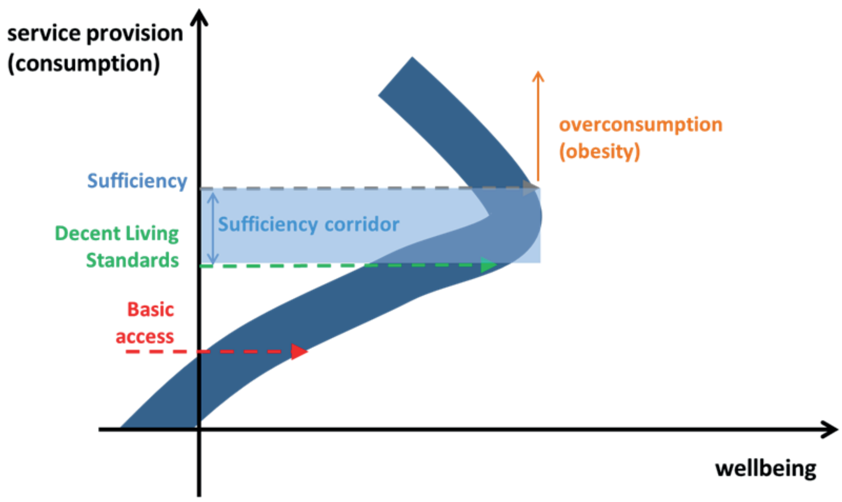


Figure 13. Stylized relationship between levels of service provisioning and human wellbeing. Different thresholds can be differentiated on the basis of absolute levels of wellbeing as well as by the rate (elasticity) of wellbeing change to changes in service provision/consumption levels that show diminishing returns at higher levels of service consumption. Graphic courtesy of Arnulf Grubler and Caroline Zimm.

technological, social, and behavioral innovations to minimize resource use and environmental impacts, it is possible to provide higher levels of services than in DLS, that is, sufficiency, while remaining within planetary boundaries and also assure equitable access to natural resources (see the sufficiency corridor in Figure 13). An illustrative scenario for such sufficiency levels of service provision is given in Section 3.4.2 below. Lastly, there are also levels of service consumption that are so high as to diminish human wellbeing either at the level of the individual or at the level of society, labeled 'overconsumption' (obesity) in Figure 13 (not discussed separately in Section 3.2 below).

Consider the case of nutrition: food consumption (especially high energy food like fats and sugars) exceeding physiological needs, especially when combined with a lack of exercise, leads to overweight, even to obesity, a global nutritional pandemic (see also Box 6 on Malnutrition). In 2016 approximately two billion adults (~40%) worldwide were considered overweight, and 650 million (13%) were classified as obese (WHO 2020b). Obesity rates in some countries approach or even surpass one third of children and adult population, for example, the USA, the Kingdom of Saudi Arabia, the Arab Republic of Egypt, and Republic of South Africa[1], and are a major health risk, reducing life expectancy and thus wellbeing of those affected. At the same time, over 800 million people go hungry and over 150 million children are stunted (WHO 2020b).

As another example consider motorized transport with privately owned vehicles: At high levels of vehicle ownership and use, particularly in densely populated urban environments, the benefits of a convenient and flexible individual mode of transport are quickly counterbalanced by congestion, urban air pollution and noise that diminishes not only the utility of vehicle ownership and use, but also the wellbeing of the individual car user and all urban residents. A high level of consumption that is therefore neither efficient in terms of individual wellbeing nor in terms of Pareto efficiency is classified as 'overconsumption' (obesity) in the discussion here.

3.2. Providing useful services to improve wellbeing while reducing resource needs

3.2.1. Introduction

This chapter uses 'services' as an analytical entry point into the challenge of rapid sustainable transformation. Services include nutrition, mobility, shelter and thermal comfort, entertainment, and socializing, all of which provide for human needs and wellbeing. The provisioning systems which deliver these services require energy, material, and land resource inputs. The use of these resources—particularly in the form of fossil fuel combustion, agricultural practices, and forest conversion—generate GHG emissions and other forms of pollution which undermine wellbeing and the future capacity of provisioning systems to meet human needs. Services are therefore a bridge between human needs and wellbeing on the one hand, and resource use by provisioning systems on the other (Figure 14) and therefore are the central metric adopted in this chapter.

From this perspective, the pivotal challenge for sustainable transformation is: How can more services be delivered using fewer resources in order to satisfy all human needs and improve wellbeing? Figure 14 shows the basic organizing framework used in this chapter. It has four main building blocks: human needs and wellbeing, useful services, service-provisioning (delivery) systems, and resource inputs.

Figure 14 also shows three dynamic constraints or pressures which require change in how resources are converted through provisioning systems into useful services to meet human needs. These constraints define the challenge of sustainable transformation: downward constraint on resource use (e.g., planetary boundaries), minimum thresholds and upward constraint on needs satisfaction (see Sections 3.2.2 and 3.2.3 below), and downward constraint on service consumption (sufficiency, see Section 3.2.4 below).

We discuss each of the constituents of Figure 14 in more detail below.

Human needs and wellbeing

Providing for human needs is at the heart of sustainable development. There are many different conceptual and empirical approaches to needs. Maslow (1943) conceptualized a widely used hierarchy of needs which distinguished 'basic' needs for food, shelter, and security, 'intermediate' needs for belonging, connectedness, and self-esteem, and 'higher' needs for self-actualization including through learning, creativity, and morality. This hierarchy is shown as the pyramid in Figure 14. Max-Neef (1992) developed a similar typology of fundamental human needs consisting of subsistence, protection, creation, freedom, leisure, identity, understanding, and participation. How these needs are satisfied is determined differently by individuals and groups, and with widely varying implications for resource consumption and sustainability (Vita et al. 2019).

Satisfying needs ensures human wellbeing and quality of life. There are two distinct conceptualizations of wellbeing: hedonic and eudaemonic. Hedonic wellbeing is a subjective state of motivation and pleasure, linked to happiness and life satisfaction, and is commonly measured (subjectively) through self-reports. Eudaemonic wellbeing is associated with

1 For readability, only 'South Africa' will be used in the remainder of this report.

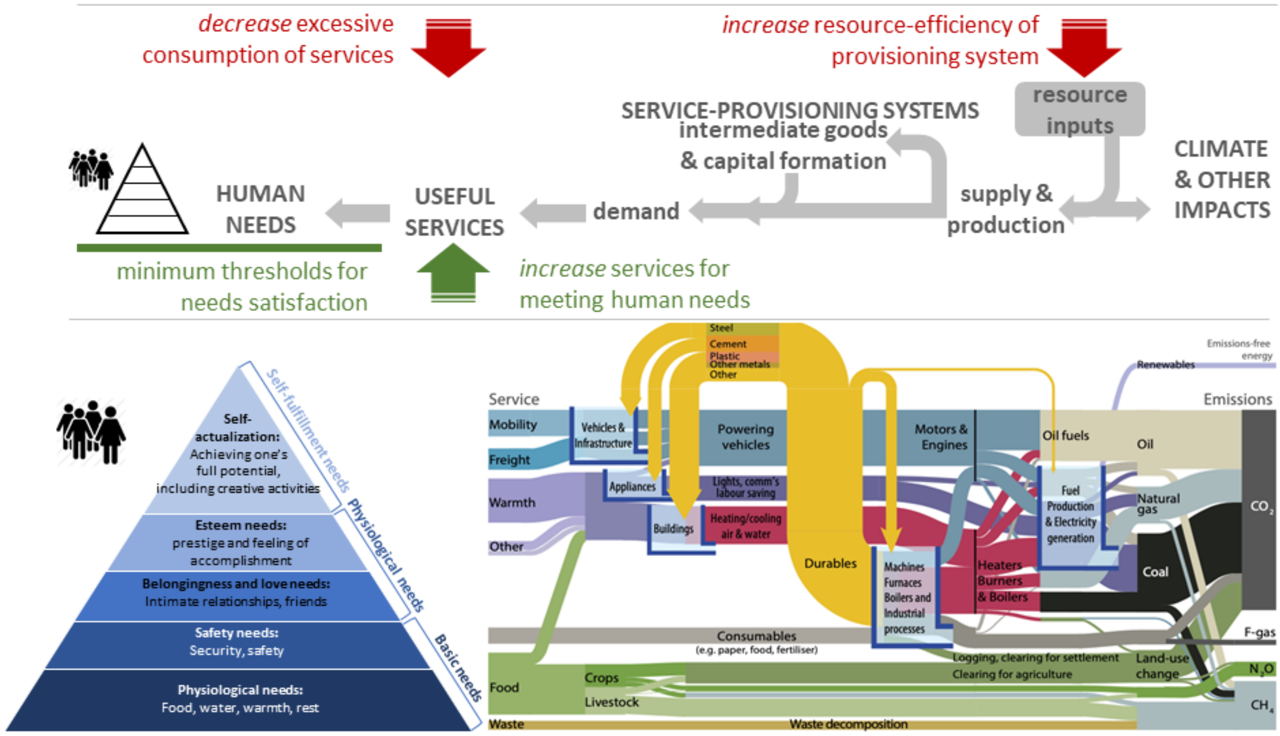


Figure 14. Transforming the provision of services to meet human needs with fewer resource inputs. Sources: Needs based on Maslow (1943) and resource processing flow (Sankey) diagram from Bajželj et al. (2013).

fulfillment and self-realization, and places greater emphasis on the social and material context enabling people to flourish. Eudaemonic wellbeing is embedded in development strategies to enhance human capabilities (Sen 2001) or otherwise meet human needs (Doyal and Gough 1984).

Useful services

People consume useful services to fulfill their needs. More traditional economic concepts of 'demand' apply to bundles of goods (and services) acquired through market or nonmarket transactions. But demand is an intermediate not a final step. Human needs are met by the useful services provided by demand (Grubler et al. 2012b).

As an example, demand for cars, fuel, and roads is an intermediate step toward providing the useful service of mobility. Mobility, not cars, meets people's needs to move around in order to work, socialize, and recreate. Passenger-kilometers of mobility is a direct measure of useful service, rather than numbers of cars or quantities of fuel. Evidently, delivery of useful services requires technologies (vehicles), infrastructure (roads, bridges), and resources (fuels). These can also be framed through the service lens (e.g., ton-km for goods transport), but they do not directly provide for human wellbeing and are thus considered necessary but ancillary services required for the delivery of useful services.

The application of service concepts to environmental and sustainability challenges originates in the energy literature (Nakicenovic et al. 1993, Nakicenovic et al. 1996). Globally, only 14% of the energy resources harvested from nature deliver useful services to final users (72 of 511 EJ, see Section 3.4 below)—the remaining 86% is wasted (De Stercke 2014). Although there are thermodynamic limits on how much this wastage can be reduced, there are still enormous potentials for improving the efficiency of the global energy system as a service-provisioning system to meet human needs (Cullen et al. 2011).

More recently, the narrow emphasis on energy has broadened to include materials and other resources. As a decarbonizing world sees energy supply systems relying ever less on fossil fuels, the consumption of materials, biomass, land, and other resource inputs will increase the burden on the natural environment. The term 'resource-intensive services' better captures this broadened focus, although 'energy services' is often used interchangeably.

Service-provisioning systems

Focusing on useful services is important as it is a direct antecedent of needs satisfaction. From a sustainable transformation perspective, focusing on useful services also helps broaden the solution space beyond demand and resource-efficient goods to embrace the many alternative ways in which useful services can be delivered through provisioning systems.

Provisioning systems are those that make useful services available at the point of consumption. They include a wide variety of actors (e.g., manufacturers, internet start-ups) operating in institutional (e.g., markets, regulatory frameworks) and material contexts (e.g., factories, transport networks).

As shown in Figure 14, provisioning systems consume energy, material, land, and other resources to deliver useful services. These resources are converted through physical supply chains into a usable form in domestic and other settings. Figure 15 provides a schematic illustration for a typical European household.

As articulated in this chapter, the central challenge for sustainable transformation is to reduce the resource requirements of service-provisioning systems while expanding the capacity of those systems to deliver useful services to meet human needs.

Resources inputs

Energy, materials, biomass, and other resources consumed by service-provisioning systems cause GHG emissions and other environmental problems. Using Max-Neef's needs typology, Vita et al. (2019), found that meeting human needs for subsistence and protection accounted for nearly half of global carbon emissions, with most of the remaining emissions accounted for by freedom, identity, creation, and leisure needs. Meeting needs for understanding and participation accounted for less than 4% of global emissions.

Sankey diagrams capture how resource inputs are converted into useful services by provisioning systems, and the inefficiencies and losses at each conversion step (Cullen and Allwood 2010). Figure 14 shows a Sankey diagram modified to also show the GHG emissions (far right of Figure 14) from the use of resources (right of Figure 14) to deliver useful services (far left of Figure 14). As this is a snapshot of global emissions in 2010, the resource impacts of global service-provisioning systems are dominated by fossil fuel combustion and land-use change.

Constraints or pressures for sustainable transformation

The basic organizing framework for this chapter shown in Figure 14 describes human needs being satisfied by useful services made available by service-provisioning systems which require resource inputs. Objectives for sustainable transformation can be overlaid on the basic framework in the form of dynamic constraints or pressures. These are shown as arrows in Figure 14. The constraints are dynamic for two reasons. First, they are culturally, politically, and technologically defined and these landscapes are ever changing. Second, the constraints generally define directions of travel not fixed destinations. Constraints can push service delivery both upwards, for example, when considering the development objectives of poverty eradication and more equal access to service provided, or downwards, for example, by either reducing resource use, overutilization of global commons (atmosphere nutrient cycles), or overconsumption. Absolute constraints are represented by planetary boundaries that relate to climate change and global nutrient cycles. Taken together, these constraints ultimately influence both levels of resource use and associated services provided and hence human wellbeing. The only policy variable operating within these constraints is efficiency of service delivery and resource use which can be significantly improved through behavioral, market, and technological innovation.

Downward constraints on resource use

Use of finite or scarce energy, material, land and, other resources must be reduced to address climate and other environmental impacts of service-provisioning systems. There are many strategies for improving the efficiency with which service-provisioning systems convert resources into useful services. These include:

- *demand-side strategies* which change how services are delivered (e.g., more energy-efficient end-use technologies and passive systems, digitalization, business models to increase utilization rates);
- *supply-side strategies* which change how resources are converted (e.g., precision agriculture, decarbonization of power production) and how intermediate goods and capital are formed (e.g., net-zero energy buildings, circular economies, dematerialization, urban design).

While both strategies are interdependent and mutually contingent, this report focuses on the demand-side of service-provisioning systems, while recognizing and discussing the interdependencies between demand-side and 'upstream' supply-side transformations. The reason for this focus is twofold. Firstly, the linkages between services provided and human wellbeing under planetary boundaries (and thus the SDGs) are most direct and apparent on the demand-side. Secondly, in analysis, modeling, as well as in current policy frameworks, demand-side perspectives and options remain significantly underrepresented (Grubler et al. 2012a). As such synergistic effects with the SDGs remain underexplored, as supply-side strategies tend to have more SDG trade-offs than synergies (see Section 3.4.3 below).

Constraints on services provided

Upward and downward pressures on services provided are discussed in more detail in the following Sections 3.2.2 to 3.2.4. Upwards pressures, that is, the need to increase service provision, are discussed in Section 3.2.2 on basic access and in Section 3.2.3 on decent living standards for all. Downwards pressures either on levels of resource use or service provision (or both) are discussed in Section 3.2.4 on sufficiency below.

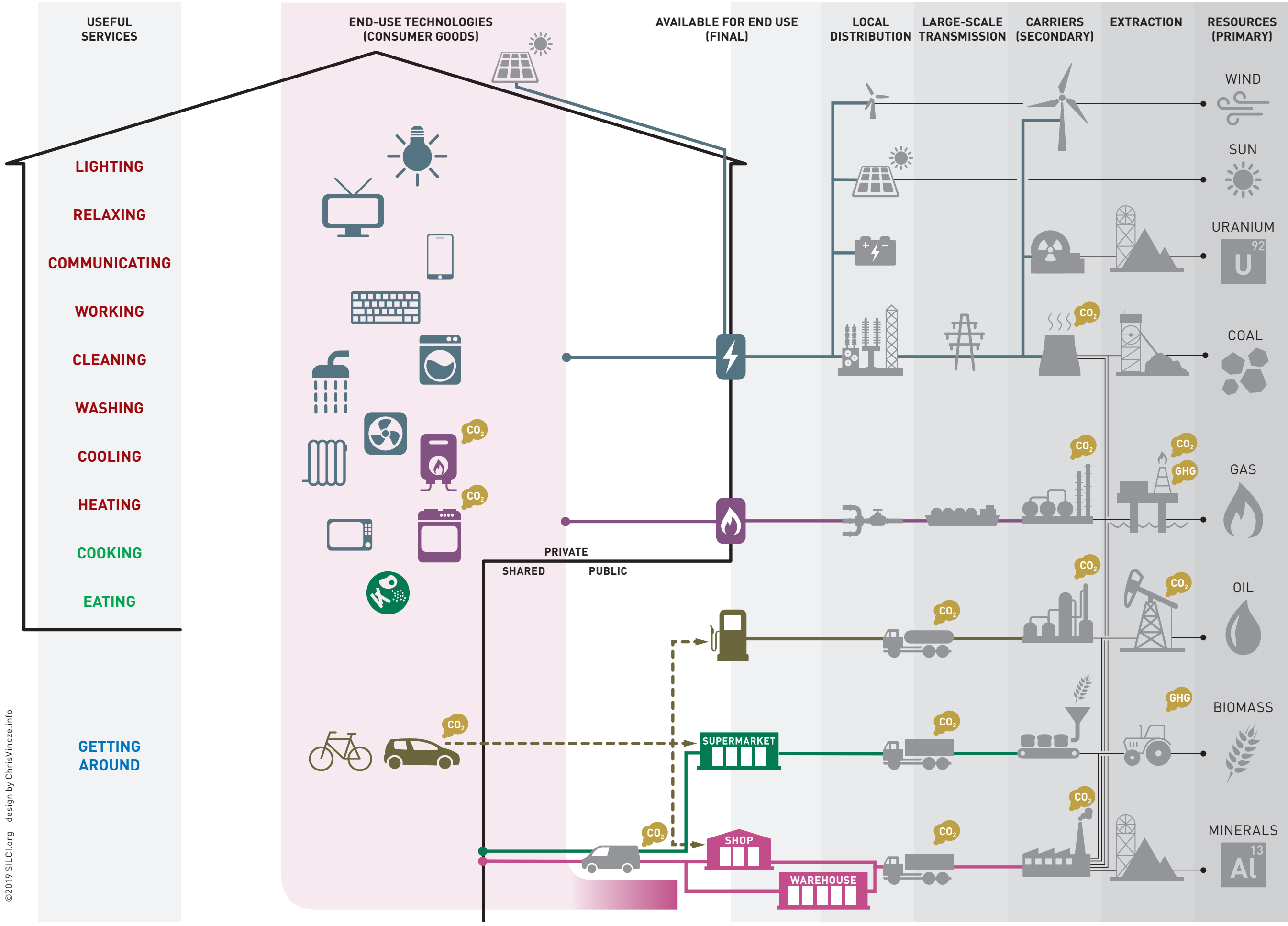


Figure 15. Resource conversion chains as part of the provisioning system for useful services including heating, cooking, and mobility (illustrative for a typical European household). Source: Wilson et al. (2020b).

3.2.2. Basic access to modern services in low-income countries

Access to basic goods, services, and freedom are fundamental to human wellbeing and development. Minimum needs baskets to eradicate deprivation and poverty universally have been discussed in the literature, such as in *A Theory of Human Needs* (Doyal and Gough 1984) and *Decent Living Standards* (Rao and Min 2018). The UN 2030 Agenda also provides a broad framework that targets inclusive, equitable and universal access to basic infrastructure and services that mirror the minimum needs baskets identified in the literature. Figure 16 provides an overview of the current status of progress globally on some of these basic access indicators. What is evident from the figure is that access to these services is highly unequal across populations and across goals. National and regional differences are also vast and are further magnified when assessing differences subnationally between provinces, urban/rural, and population subgroups. While accelerated progress has been made in some regions since 2015, for certain goals, regions, and nations, in particular, the gaps between ambition level and current achievement is significant. For instance, the *UN Sustainable Development Goals Report 2019* highlights:

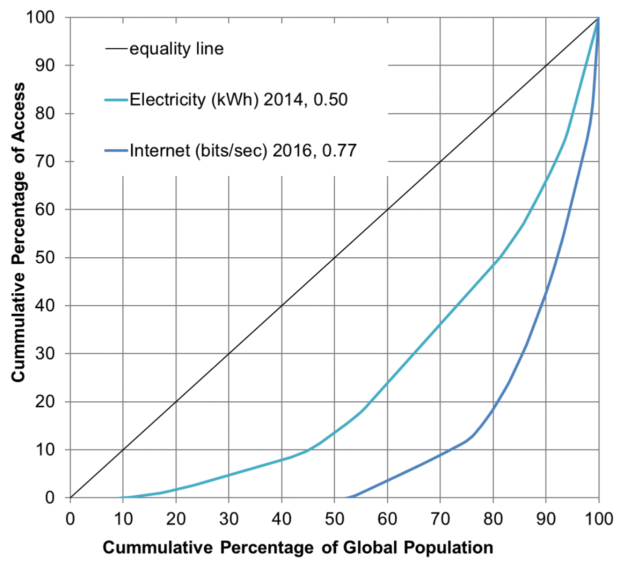
- Almost half of the world's population have no access to social protection (SDG1)
- Two thirds of more than 820 million undernourished people live in South Asia and sub-Saharan Africa (SDG2) (see also Box 6)
- About a third of the global population lacks access to basic medical coverage (SDG3) (see also Box 7).
- More than half of the schools in sub-Saharan Africa do not have access to basic drinking water, handwashing facilities, the Internet, or computers (SDG4)
- In South Asia, 30% of women aged 20 to 24 years are married before age 18 (SDG5)
- A quarter of health care facilities worldwide lack basic drinking water services (SDG6)
- About 3 billion people lack access to clean cooking fuels and technology (SDG7)
- One fifth of all young people are not in education, employment, or training (SDG8)

- Only about half of the world's population currently use the Internet (SDG9)
- In many countries an increasing share of national income goes to the top 1% (SDG10)
- Globally, 2 billion people do not have access to waste collection services (SDG11)
- The material footprint per capita in high-income countries is 13 times the level of low-income countries and exceeds their domestic material consumption (SDG12)
- About 70% of detected victims of human trafficking are women and girls (SDG16).

Figure 16 summarizes current global inequalities in access to basic service provision and the corresponding numbers of people lacking access.

Despite the undisputed value placed on expanding access to basic goods and services for all, at current levels of implementation, investment, and policies, many countries will not achieve the goals by 2030. Achieving the goals will require additional capacities, improved governance, and increased investments. According to one rough estimate, globally \$5–7 trillion of annual investment is required for building the infrastructure needed to meet basic needs including roads, rail and ports, power stations, water and sanitation, food security, climate change mitigation and adaptation, health, and education by 2030 (UNCTAD 2014). In Asia-Pacific developing countries, the UN *Economic and Social Commission for Asia and the Pacific* (ESCAP) Economic and Social Survey 2019, finds that an additional investment of \$1.5 trillion per year is needed to end extreme poverty through universal health coverage, quality education, and enabling infrastructure. While the scale of investments needed are large, these are a small share of global GDP. Efforts to extend access to basic services more efficiently are also a way to reduce the scale of system capacity expansions required and investments needed (Grubler et al. 2018). In addition, there are significant synergies or spillover effects between social services, so that interventions in any one of these will have impact on others. Tapping these synergies is another way to reduce needed investments (see e.g., Dagnachew and Poblete-Cazaneve (in preparation)).

Bridging the achievement gaps also requires new approaches that go beyond just extending supply or merely providing connections to consider additional dimensions of access. Integrated planning for service provision requires linking supply to broader developmental and socioeconomic objectives. Providing access to basic services is a fundamental first step to enhancing wellbeing. But extending access to education, health care, water, sanitation, food, shelter/housing, energy, and other basic goods and services alone is not enough, unless it is affordable, reliable, of good quality, and sustainable.



Service/Technology	Population w/o access			
	Year	bn	%	Gini
Adequate urban housing+	2016	1.0	23	0.23
Secure food supply	2017	2.0	26	0.26
Safely managed water	2017	2.2	29	0.29
Mobile phones	2017	2.2	29	0.29
Banking services	2017	2.4	32	0.32
Clean cooking	2017	3.1	41	0.41
Essential health services	2017	3.8	50	0.50
Electricity (kWh)*	2014	0.5	10	0.50
Bicycles*	2014	2.5	45	0.54
Safely managed sanitation	2017	4.2	55	0.55
Internet (bits/sec)*	2016	3.0	52	0.77

+Only covering urban population.
**Smaller sample size of 80% of global population; consumption levels available leading to Ginis higher than non-access rates.*

Figure 16. International inequality in access to and use of basic goods and services essential for human wellbeing. Left panel: International Lorenz curves and Gini coefficients accounting for the share of population without access (distance between the origin and the start of the Lorenz curves on the y-axis) for select infrastructure service consumption. The 45° line represents the equality line where goods are distributed equally across the global population. The Gini coefficients represent the ratio of the areas between the equality line and Lorenz curves and the total area under the equality line. The higher the Gini coefficient, the more unequal the distribution. Right panel: number of people without access, access rates, and Gini coefficients for basic goods and services. Where no consumption level is available the share of population without access is equivalent to the Gini coefficient. Source: Adapted from Zimm (2019), updated using UN, WHO and WB data.

Box 6. Malnutrition.

Globally, malnutrition is related to some of the largest noncommunicable diseases mankind is suffering from. More than 820 million people, most of them in sub-Saharan Africa and South Asia, still regularly go hungry while at the same time some 679 million adults are obese (WHO 2020b). Malnutrition is not only related to premature death but also to substantial impairment of wellbeing, work productivity, and cognitive development. According to the World Health Organization (WHO) malnutrition refers to deficiencies, excesses, or imbalances in a person's intake of energy and/or nutrients. Undernutrition leads to stunting, wasting, and underweight. The prevalence of undernourishment has been rising since 2014 (FAO 2019). This rise is attributable to a continuation of poor economic access to food compounded by factors such as extreme weather events, political instability and conflict, as well as economic volatility. Prevalence of malnutrition is mostly concentrated in Asia (515 million people) and sub-Saharan Africa (239 million people) (FAO 2017). In sub-Saharan Africa the percentage of the total population undernourished is 23% mostly due to poverty and inefficiencies in agricultural value chains. Some 1.5 billion people are deficient in micronutrients. One in five children under the age of five are stunted as a result of receiving insufficient calories, proteins, and micronutrients, with lifelong implications for their wellbeing and productive potential (GNR 2018). Ironically, half of those malnourished are associated with poverty of small-sized farming lacking the means to purchase inputs for their operations leading to declining soil fertility and resilience (IFPRI 2015 cited in Hazell and Rahman (2014)). Some 33% of women of reproductive age are affected by anemia, with serious implications for their health and that of their children (Wirth et al. 2017).

Although obesity has become an epidemic causing major public health issues in developed countries mostly affecting the less educated strata of society (OECD 2017), it is on a steep rise in metropolitan areas of emerging economies. Globally, some two billion people are overweight, of whom 679 million are obese (WHO 2020b). Together these contribute to diet-related noncommunicable disease outcomes such as heart disease, stroke, diabetes, and cancer. The latter diseases are projected to become the dominant cause of death in the decades to come (GBD projections) (Mathers and Loncar 2006, Hughes et al. 2011), placing a heavy financial and operational burden on health services and reducing productive potential for both developing and developed countries. Obesity in young children is hard to reverse once acquired. Many low-income communities in urban areas consume predominantly ultra-processed foods and beverages sold at fast-food and small retail outlets, often because they live in so-called 'food deserts'—low-income areas where these are the only available foods (Popkin 2019). However, according to recent research, obesity is no longer purely a phenomenon in urban populations with more than 55% of the global rise in mean BMI from 1985 to 2017, and more than 80% in some low- and middle-income regions, due to increases in rural areas (Bixby et al. 2019).

Both forms of malnutrition are occurring unnecessarily and relate to a massive policy coordination failure within and across countries. Many countries face both undernutrition and obesity, thus bearing a double burden of malnutrition. One policy failure relates to distributional issues pointing to the need for an integrated approach to nutrition that enhances economic and physical access to foods that are not only sufficient in calorie terms, but also healthy. Undernutrition in poor countries should not be replaced by excessive consumption of low-quality calories, in particular processed foods. The other policy failure lies with insufficient supply amid a huge biophysical supply potential, inefficiencies and waste in supply chains, and distributional issues. Today, the provisioning service potential from nature to produce enough food, feed, and fiber for all would be sufficient to sustain even a doubling of the global population. From a pure calories supply point of view there should be enough food available on a global level, however, it is unequally distributed (GNR 2020). Long-run projections suggest that by 2050 the world's agricultural lands and aquatic food supply systems could produce enough food for all, while at the same time safeguarding major environmental resources (FOLU 2019). This suggests that even a concerted action of incremental adjustments in the global food system could deliver acceptable sustainability outcomes. A more transformational approach overhauling the entire food system, demands, and embarking on bold conservations and restoration goals could deliver truly sustainable outcomes well within planetary boundaries.

Efforts to expand access to electricity in sub-Saharan Africa, for example, are often highlighted as insufficient because these have not kept pace with population growth in the region. Despite this, looking at national estimates of new connections over the last five years would suggest that between 2014 and 2019 more than 115 million people gained access to electricity in sub-Saharan Africa. This implies accelerated progress since the 2030 Agenda came into force, though not yet at the pace required to meet the goal. Looking at progress subnationally, though, highlights vast differences in the pace of providing access across provinces and regions (Falchetta et al. 2019). However, of even more concern is the fact that even among those with access to electricity, a vast distribution across access quality tiers exists (Falchetta et al. 2020). For example, in some countries, where rapid growth in electricity access has been reported (e.g., Kenya), the estimated final use among newly electrified households remains very limited and is growing very slowly (Fobi et al. 2018). Such low levels of use suggest that people have not moved beyond subsistence use for lighting and phone charging to levels of demand that provide a means of livelihood through productive uses, enhanced employment, education, and income earning opportunities. Such low levels of use are attributable to an overemphasis on increasing connections without ensuring that the access provided is also reliable and affordable.

Accelerating efforts to provide reliable and affordable access to basic services requires rapid innovation in technologies, financing, and distribution models. Disruptive and digital technologies can increase access

Box 7. Universal health coverage.

Health is essential for the basic principles of equity and sustainability of the 2030 Agenda. SDG3 on health and wellbeing includes a target on u-universal health coverage which is the best preparedness element for any health event, including pandemics.

The response to the COVID-19 pandemic is one of the most practical examples of the importance of primary health care in a high-quality, universal and effective health system. The surveillance and monitoring function of the primary health care system was fundamental to identify and characterize the threat in China and elsewhere. Primary health care medical units also were the first line of action for testing, providing clinical treatment directions, and to refer cases to more complex health care facilities. This has been a common factor in the response, and most probably a key factor in the success in controlling the epidemic. Also, the primary health care system will be important in the exit strategy, the recovery stage, and to deliver the ultimate solutions, such as a vaccine.

This is not new in the public health arena. Since the Declaration of Alma-Ata (WHO), the relevance of primary health care has been recognized and was renewed and well stated at the 2018 'Declaration of Astana' that emerged from the Global Conference on Primary Health Care: *From Alma-Ata towards universal health coverage and the SDGs*. The Declaration "affirm[s] the commitment to the fundamental right of every human being to the enjoyment of the highest attainable standard of health without distinction of any kind. Convening on the fortieth anniversary of the Declaration of Alma-Ata, we reaffirm our commitment to all its values and principles, in particular to justice and solidarity, and we underline the importance of health for peace, security and socioeconomic development, and their interdependence."

All health systems have been put under stress during the COVID-19 pandemic, and the very basic principle of universal access to a quality health system is an essential element in the response. Actually, most of the global first response was to guarantee full access to the health system for the entire population—an action everyone hopes will be maintained following the pandemic. That will be the best way to address the SDG target 3.8 *"Achieve universal health coverage, including financial risk protection, access to quality essential health-care services and access to safe, effective, quality and affordable essential medicines and vaccines for all"*. The fulfillment of this target will be the best way to establish a permanent preparedness for any future event of this magnitude, which can be expected due the current challenges posed by the various global changes that are on the way, such as climate change, loss of biodiversity, unsustainable urbanization, to name a few.

This particular area requires a greater attention and special efforts to achieve the 2030 target. As can be seen from the estimate from the Institute for Health Metrics and Evaluation (IHME) (Figure 17), in the current pace the universal health care target will not be met by 2030 for many countries, and that ultimately means a less safe world for all, and human and health insecurity for a large part of the world population.

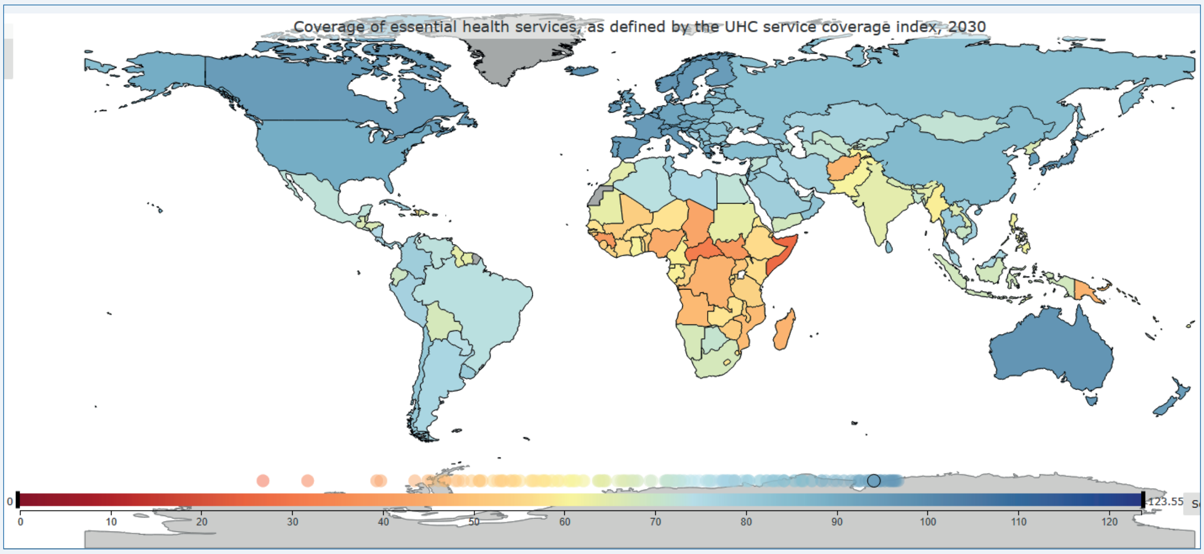


Figure 17. Achievement of health-related SDGs. Source: Institute for Health Metrics and Evaluation (IHME), http://vizhub.healthdata.org/sdg.

to basic goods and services, and directly contribute to achieving many of the SDGs (TWI2050 2019). Recent innovations in ICT, particularly mobile phones and virtual financial services provide a powerful platform to deliver essential services like e-governance, education, health, energy, water, and financial inclusion (Alstone et al. 2015). Some key areas where such innovations are already having impact are:

- Monitoring, tracking, estimation, and reporting of multiple access dimensions and latent demand. Recent efforts have used satellite datasets and mobile phones to estimate road quality (Cadamuro et al. 2019), electricity supply outages (Correa et al. 2018), and latent demand for electricity (Fobi et al. 2018, Falchetta et al. 2020).

- Options for providing services through more decentralized infrastructure in combination with highly efficient appliances and equipment that are more granular in nature and easier to scale up and diffuse (Wilson et al. 2020b). For example, direct current (DC) appliances and productive equipment in conjunction with off-grid solar energy technologies are increasingly being seen as a potential way to provide reliable and affordable energy services even to remote rural communities within the 2030 timeframe (Phadke et al. 2017).
- Demand management, for example, enhancement (where demand is low) and contraction (where demand is high) through efficiency measures, behavioral nudges and shared economy applications via information dissemination, and virtual financing options to end-users and customers (Hilty and Aebischer 2015).

3.2.3. Decent living standards and resource requirements

Going beyond providing access to basic services (see Section 3.2.2) and further raising living standards in developing countries is central to the sustainable development pathways of TWI2050. The concept of wellbeing includes that everyone has the means to pursue a decent life, and avoid harm from extreme weather, disease, and pollution (Doyal and Gough 1984). Everybody should have amenities that ensure good health, and that enable people to engage with society. This includes safe and uncramped shelter, adequate nutrition and water supply, clothing, health care, and basic comforts in the home, such as lighting and thermal comfort (including water heating), refrigerators, and clean cooking devices. In engaging with society, people seek knowledge about the world, and the means to communicate with others, which gives rise to the need for education, devices in the home to communicate (e.g., mobile phones) and access to broadcast media (e.g., television), and access to mobility.

Research has shown that high levels of wellbeing measured with different indices or indicators, such as the Human Development Indicator (Steckel et al. 2013), access rates to basic services, average income, or life expectancy which can be achieved with different levels of environmental impacts (e.g., GHG emissions) (Lamb and Rao 2015, UNDP 2015). This very high elasticity of wellbeing gives hope to providing DLS in line with the SDGs for all of humanity with overall lower resource requirements and lower negative impacts on Earth systems. This means that developing countries can embrace a low-carbon transformation in their convergence with wellbeing levels of industrialized countries (Ürge-Vorsatz et al. 2014, Stechow et al. 2015). Overconsumption is currently pervasive in industrialized countries and high-income economic strata of developing countries.

The components of a decent life are reasonably well established in literature (Alkire and Santos 2014, Alkire and Robles 2017). The exact quantities of such living standards are subjective and vary across individuals' and households' choices, cultures, time, and location. Yet, there is enough commonality across humanity to identify a minimum set of core requirements (Doyal and Gough 1984, Rao and Min 2018). Trying to provide a first generalization, Rao and Min (2018) developed a framework and provided rough guidelines for the quantities of people's requirements, where possible (Figure 18). This is what we call 'decent living standards (DLS).'

Translating the DLS concept into tangible indicators and thresholds, they cover physical and social wellbeing and the necessary goods and services available at household and community level. The household level covers the following categories:

- *Nutrition includes food and cold storage*. DLS food requirements are specified in kcal per capita per day, and aggregated based on the population structure of each country (men, women, and children have different calorie requirements). People need the opportunity to follow an adequate, nutritious, and balanced diet with a limited share of meat derived calories. Ongoing work is already going beyond calories to include micronutrients (e.g., DeFries et al. (2018) for India). Availability of a refrigerator to store food produce is accounted for.
- *Shelter and living conditions.* Durable walls and roof and a minimum size of 30m2 for a household (or 10m2 per person) to accommodate a bathroom and kitchen in an uncramped manner. Basic comforts include electricity and clean cooking devices, and inhouse sanitation and freshwater access, and devices to provide thermal comfort and hot water, if applicable (e.g., fans, heating, or air-conditioning). Adequate lighting and household appliances (see other categories).
- *Clothing*. Minimal material requirements to dress oneself suitable to the prevailing climate.
- Information and communication. One mobile phone per adult and one television set per household to enable communication, information, and participation.
- *Mobility*. Everyone should have access to motorized transport, either from private or public modes, depending on local starting conditions, while at the same time minimizing pollution and hazards to health. Without mobility options, people are severely limited in their livelihood opportunities.

These household-level goods and services are supplemented by community-level DLS components

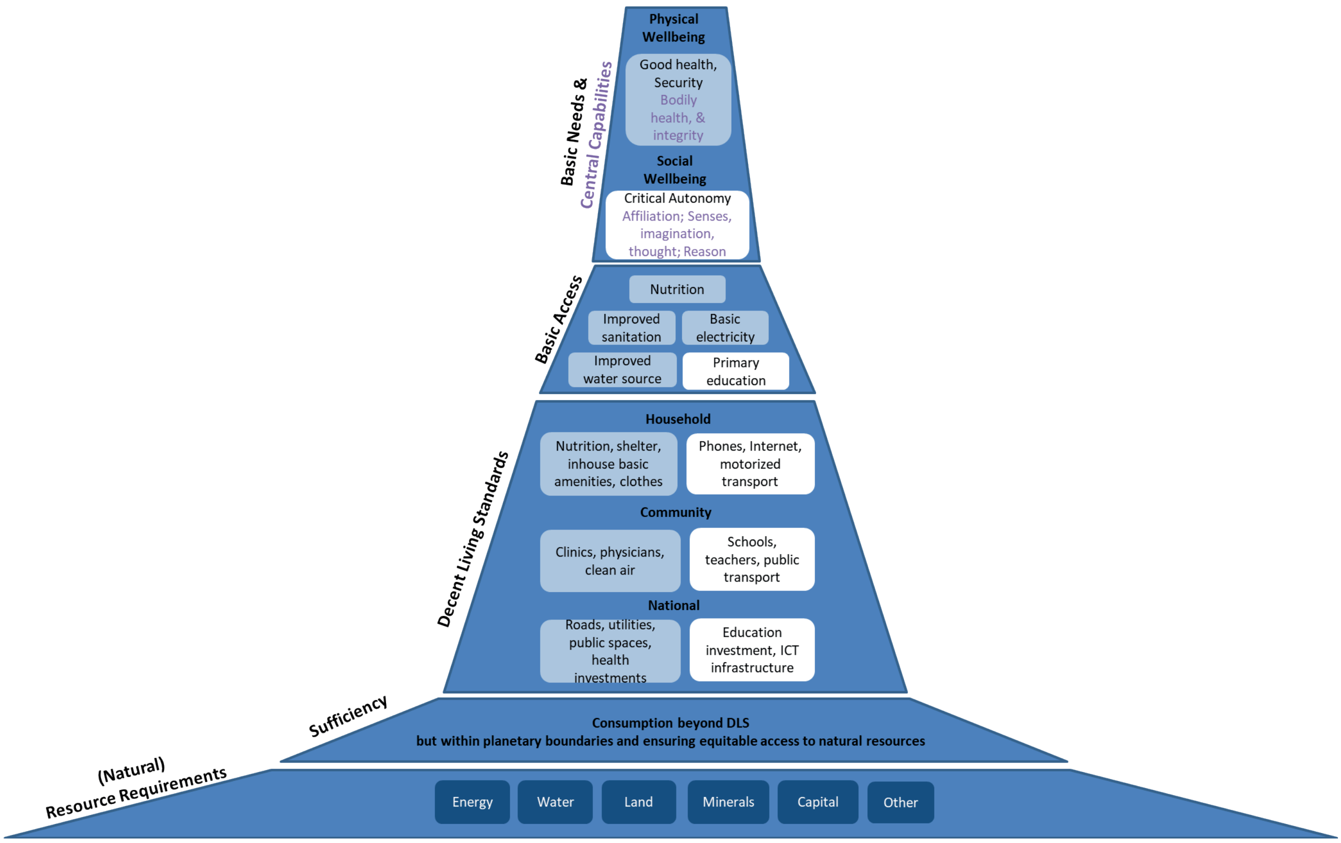


Figure 18. Decent living standards (DLS): hierarchy of material requirements and their derivation. We use the concept of Doyal and Gough (1991) for basic needs and Nussbaum (2000) for central capabilities to define physical and social wellbeing, for which the DLS serve as prerequisites. Source: Adapted from Rao and Min (2018). Graphic courtesy of Caroline Zimm.

to help people develop their capabilities and thrive: accessible and adequate health care services (see Box 7), primary and secondary education, and public infrastructure (electricity, water, sewage, public transport and road infrastructure, ICT network).

The DLS are universal, minimum requirements. They have commonalities across countries but also follow local peculiarities when being operationalized intro country-specific thresholds. A universal standard for adequate floor space, durable housing, and thermal comfort translates to regionally different construction materials and space heating and cooling requirements (Rao et al. 2019). These vary with heating and cooling degree days, which can be estimated from nationally-averaged, population-weighted data, accounting for future climate change impacts. The energy intensity of supplying water to households depends upon national water scarcity. Similar differences apply to modal choice or diets. The material requirements to achieve DLS for all in the near-term future in different countries thus differ with their distinctive starting conditions in each sector.

Rao et al. (2019) have made an assessment for different scenarios for India, Brazil, and South Africa, using the following illustrative service thresholds:

The DLS include a sufficient amount of an average of 2,500 kcal per person (accounting for age and gender) with the share of animal protein differing across countries. This is already a deviation from current household data that shows food deprivation in many households. To go beyond this toward healthy diets, micronutrient deficiency (e.g., zinc) of poor diets requires diet shifts.

The annual energy demand for a household would be around 1 MWh and would cover an LPG cookstove (45% efficiency), an LCD television set, phone charging and electric lighting with a minimum illuminance level of 150 lux, and a 150 liter refrigerator. Thermal energy requirements in terms of water heating, air-conditioning or heating would be additional depending on climatic conditions. Future efficiency improvements and long lifetimes for all appliances play an important role in reducing overall energy and material demand and costs. For example, currently only 25%–32% of households use LEDs for lighting in India, Brazil, and South Africa.

Inhouse sanitation facilities and a minimum quantity of 65 liters per capita per day (a generous interpretation of Gleick (1996)) in running water are accounted for. Clothing and footwear is based on observed household survey quantities. This translates to 1.3 kg of clothing and 0.9 kg of footwear in India versus 2.3 kg of clothing and 1.4 kg of footwear in Brazil.

Two archetypes for rural and urban low-energy housing respectively (Mastrucci and Rao 2019) that use local and durable materials and construction practices and building configurations (Paulsen and Sposto 2013, Bansal et al. 2014, Nix et al. 2015) are provided. In rural areas, this is a single-story masonry structure, and in urban areas a four-story reinforced concrete structure. Energy-saving measures to reduce both construction and operational energy include aerated concrete blocks for masonry instead of fire bricks, and filler slabs instead of concrete slabs for roofing and roof insulation. Metal roofs are common for low-income permanent buildings in South Africa and India, for example, but they offer a significantly lower protection level to heat and cold compared to other solutions, potentially entailing increased health risks.

The mobility needs (in terms of distance) of a society are hard to define at a global scale because they are very place-specific and have grown historically. Overall, a minimum mobility of 10,000 passenger-km is derived from earlier work, which is roughly based on the average transport demand in an efficient, dense but affluent economy, i.e. (Japan (Rao and Baer 2012). This also allows for leisure travel. How such mobility demand is met depends on existing preferences, public transport options, and infrastructure. In India, currently two-wheelers are dominating the stock of light-duty vehicles (73%). With increasing wealth, passenger cars will likely catch up. In sustainable scenarios, public transport plays a large role to minimize air pollution, GHG emissions, and material demand for cars.

What are the energy requirements for the provision of these DLS today and for different future scenarios? Currently, DLS reveal the prevailing extent of multidimensional poverty (Rao et al. 2019) with more people lacking DLS than the number of income poor, as defined by the World Bank's International Poverty Line (2011 PPP $1.90 per day). In India, 15%–93% of the population lack various elements of DLS, in contrast to 20% of income poor; for example, more than 93% (over a billion) of Indians lack access to space-cooling to avoid heat-induced health effects (Mastrucci et al. 2019). Box 8 provides an assessment of global future DLS energy demand for humanity.

The lifestyles people adopt as their wellbeing increases will influence material and energy demand growth (Creutzig et al. 2018). Means of social affiliation, including basic education and access to broadband and social media, require just a few gigajoules of energy per capita. Future construction energy and material demand could be avoided if slums and poor-quality rural homes were upgraded with energy-saving housing construction practices (Mastrucci and Rao 2019), and if public transportation could meet future mobility demand.

Achieving DLS for all aims at providing everyone with these standards while reducing the overall pressure on the Earth system. A world that achieves the SDGs and additional ambitious Earth-system targets has to ensure that the world has long-term adequate resource supply to guarantee these DLS everywhere and for future generations.

The DLS are a floor, not a target or ceiling. They are far from the lifestyles prevailing in the Global North and (increasingly) wealthier populations elsewhere. But they are also a long way from anything resembling poverty. Average future living standards may exceed this level. With changes in technology, behaviors, and values, what is conceived to be decent or can be provided in a sustainable manner will change in the long run. For the coming years, however, we believe that the presented DLS provide a good basis for human wellbeing. Future work will have to go beyond energy (and meeting climate goals), to assess the quantities of materials (e.g., steel, concrete), moving toward also covering other Earth-system targets under development (e.g., by the Earth Commission and the Global Commons Alliance).[2]

3.2.4. Sufficiency in service demands and resource use

The origin of the sufficiency concept relates to the observation of decreasing marginal returns to consumption of services and goods that suggests an ultimate upper floor to consumption.

The first empirical proof of the general concept was demonstrated by German statistician Ernst Engel (1857) who demonstrated that the share of food expenditure decreases with rising incomes. Likewise Easterlin (1973) and Easterlin et al. (2010) observed that happiness or self-reported wellbeing saturates or even diminishes beyond certain income thresholds. These diminishing marginal utilities of consumption imply an upper bound on the ability of more services to meet more needs or ensure more wellbeing. It is important to note that these empirical findings typically apply to income expenditure on material goods, rather than, for example, time spent consuming services associated with the higher levels of Maslow's hierarchy, which also can (but not necessarily must) be

2 www.globalcommonsalliance.org

resource-intensive activities (e.g., when involving long-distance international travel for cultural or recreational purposes).

There are two other reasons to argue for an upper bound for services. First, if the resource costs and environmental impacts of service-provisioning systems are factored into the wellbeing calculus, then ever-higher levels of services imply ever more degradation of natural systems which undermines wellbeing for all (Knight and Rosa 2011). Second, wellbeing is seen in relative as well as absolute terms. The perceived wellbeing of others shapes people's own sense of wellbeing. The wellbeing of others cannot be observed, so is perceived through proxies such as income, material wealth, and service consumption (including nonmaterial and nonmarket services).

Box 8. Providing global decent living standards (DLS) with minimum energy.[a)]

How much energy would be needed to provide DLS (as proposed by Rao and Min (2018) universally and discussed in Section 3.2.3) to the entire global population? The technologies assumed for this scenario are either the best available today, or those likely to become available in the coming decades. For example, for residential, public, and commercial buildings, we assume a full, global deployment of the most efficient buildings currently available (with respect to heating and cooling) and, when constructing these buildings, we assume embodied energy is minimized through the choice of materials and extension of buildings' lifetimes. Assumptions like these allow us to estimate energy intensities of all the material services required to provide DLS. We also estimate the associated activity levels. In some cases, Rao and Min (2018) offer appropriate numbers. In other cases, we must produce *quantitative* and/or *disaggregated* values from their *qualitative* guidelines. Our assumptions relating to both technologies and activity levels are regionally dependent but do not vary with income or wealth. All variations in material consumption are between nations and due to differences in local climates, population densities, and the size and age structure of these populations.

What are the energy requirements of such a world? In final energy terms,[b)] we estimate that Decent Living Energy (DLE) in such a future is achievable with less than 150 EJ/year (see Figure 19). This is over 60% lower than current global consumption, despite the 2050 population being around 30% larger than the present day. Per person, this represents 15.3 GJ/year on average, with our estimates varying from 13 GJ/year in temperate countries with high population densities, to >18 GJ/year in cold, sparse areas like Central Asia. In contrast, current final energy consumption in high-consuming regions in North America, northern Europe and the Middle East is ~150–300 GJ/year per person (Oswald et al. 2020); 10–20 times larger than our DLE estimates for these regions, while world average is over 50 GJ/year per person and thus 3.3 times higher.

We can also consider how this 15.3 GJ/year per person is spread across the dimensions of decent living. Mobility and nutrition each account for about 3 GJ/year; health care, hygiene, and shelter and living (which includes heating and cooling and construction of houses) account for another 1–1.5 GJ/year each; education, clothing, and communication and information (including operation and production of laptops and phones and the networks and data centers serving them) account for a further 0.5 GJ/year each.

Finally, we note that our DLE estimate is low relative to other researchers' projections of future energy use—largely as we imagine a world of universal, DLE-based consumption. In 2050, DLE is 75% below the International Energy Agency's business-as-usual estimate and 60% below their most ambitious Beyond 2-degrees Scenario. DLE is also ~40% lower than 2050 energy use in the Low Energy Demand (LED) scenario of Grubler et al. (2018), with the difference allowing for higher levels of service provision beyond DLE ('sufficiency corridor,' Section 3.2.4 below).

The LED scenario is one of very low energy demand, and the figure inserts give some indication why DLE remains significantly lower. LED considers a transition from the present day to a world of low demand, and hence substantial regional disparities in per-capita energy use remain. Average per-capita energy use in OECD countries is close to 60 GJ/capita—more than three times larger than in the Middle East and Africa (MAF). Energy use in Eastern Europe and the former Soviet Union also remains high at over 40 GJ/capita. Variations in DLE across nations is only ~13-18 GJ/capita, and hence variations between these regions are insignificant.

Clearly our current energy consumption is far higher than is required to meet basic human need and provide the foundations for good life for all. Much current consumption is instead wasteful and not directed toward human wellbeing or indeed is directly in opposition to it. The notion of DLE provides an alternative perspective that is far more materially generous than those opposed to strong reductions in consumption often assume

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a) Based on Millward-Hopkins J, Steinberger JK, Rao ND & Oswald Y (in review). "Providing Decent Living with Minimum Energy: A Global Scenario." Global Environmental Change.

b) We use *final energy* as this better reflects the energy requirements of society and economic activity; primary energy assumes a portfolio of existing energy sources and the associated conversion losses occurring when, for example, coal is converted into electricity, or oil into gasoline. With respect to human wellbeing, final energy is still a means to various ends—but it is closer to these ends than primary energy.

(continued)

Box 8 (continued)

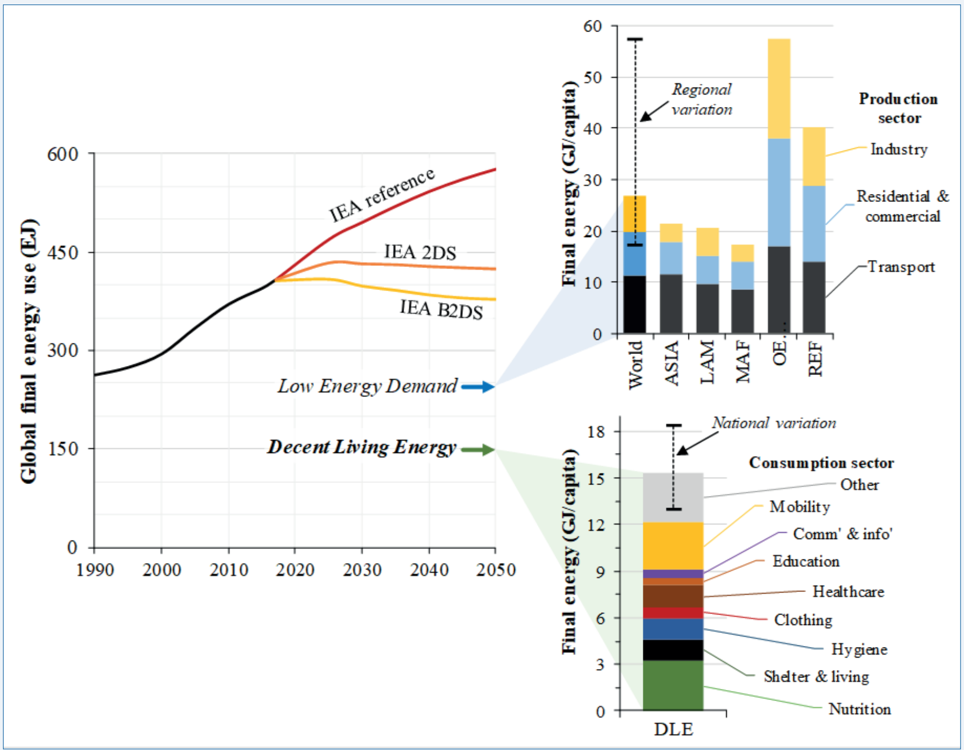

Figure 19. Comparison of global energy demand for DLS in 2050 with exemplary energy scenarios (in EJ). Source: based on Millward-Hopkins et al. (in review).

Inequalities in any of these measures can therefore undermine subjective wellbeing (Wilkinson and Pickett 2010). Globalization of media, culture, and information transmission more broadly mean that referent social groups against which people compare their own service consumption are increasingly distant elites. This further polarizes perceived inequality.

Taken together, these arguments place an upper bound on the consumption of useful services. Together with the minimum thresholds for accessing basic services and DLS, this means there is a 'safe operating space' for service-provisioning systems guarding against both excessive levels of consumption and inadequate levels of consumption, that is, a 'sufficiency corridor.'

Sufficiency is a common articulation of the upper bound to service consumption. Sufficiency means consuming less in absolute terms and is an intentional contrast to 'efficiency' which implies consuming more with less in relative terms. Sufficiency builds on longstanding concepts such as 'resource conservation' and 'curtailment' to avoid unnecessary waste but has a stronger normative meaning in which more becomes too much and is not just undesirable but is morally wrong and inequitable. For example, the concept of sufficiency has been discussed to argue for an upper bound to the level of service provision and associated resource use that is compatible with planetary boundaries, with climate targets used most frequently as examples in the literature (Friends of the Earth 2018).

A global survey of resource use and human wellbeing was conducted by O'Neill et al. (2018). In that study four planetary boundaries were downscaled to the national level to reflect heterogeneity and to determine per-capita sustainability thresholds for a sample of 150 countries to derive a planetary boundary sustainability performance indicator. Typically (with exception of water) only between 34% and 45% of countries currently remain below their per-capita sustainability threshold. The study concluded that given current performance "no country meets basic needs for its citizens at a globally sustainable level of resource use." Considering best practice (using best performing countries as a yardstick) suggests that meeting basic physical needs and access (see Section 3.2.3 above) could be met for all without transgressing planetary boundaries but the achievement of more qualitative goals of high life satisfaction (based on 11 social indicators) would require between two and six times the resource use above planetary boundaries given current average performance. From this perspective, efficiency of service provisioning will be key for defining sufficiency levels within planetary boundaries.

Box 9 reviews the (sparse) scenario literature on quantitative sufficiency levels. While global constraints on levels of service provision and resource use are an important component, they are by themselves not sufficient without also considering distributional issues, that is, the question of the heterogeneity and differences in perceptions of sufficiency and the fairness in the distribution of resource use underpinning service-provisioning systems which remain highly inequitable. Sufficiency levels can also not be discussed without due consideration of the efficiency of resource use as they determine how much service provision may be possible within planetary boundaries.

Setting expectations for sufficiency in transitions to sustainable futures must take into account not only the fundamental limitations of resources and the need to increase efficiency in their use, but it must also examine the influence of norms, beliefs, and social identities in patterns of product choice and consumption. The patterns of consumption, and with it perceptions of sufficiency, are differentiated by culture, economic, and environmental contexts. This ranges from sufficiency that means little more than an aspiration in the face of a struggle for minimal subsistence among the least advantaged to a wide set of choices of products and quantities that may support long-term societal and Earth-system wellbeing. Perception of needs and wants is modulated by awareness of opportunities, that is, the availability of goods and services. That in turn is shaped by cultural influences, social media, as well as advertising, which in order to be effective needs to be attuned to local culture and norms.

It is also important to look within a nation or a metropolis at a more granular scale of the community and a multilevel view of needs, opportunities, and abilities that influence community members' perceptions of sufficiency and thereby some of their choices for consumption. At this scale, more culturally and contextually specific information can lead to more detailed insights and recommendations on how to foster sufficiency and more sustainable outcomes. The levels can be characterized as:

- The individual or household micro level, which looks at lifestyle, social identity, economic status, and educational level of the members of the community.
- The meso level is the local social environment with its culture, norms, degree of connectedness or separation of communities, and differences in symbols and narrative expressions indicative of social identities and distinctions in status and lifestyles. Social identities and narratives which may reveal them are significant in that they also may reflect a sense of inclusion or exclusion with regard to a particular community and thus also affect motivation for acting in accord with the community, including in following patterns of greater or lesser sufficiency.
- The macro level is the state or nation and, more importantly, its institutions of commerce, regulation, and finance. These support or hinder choices that can be made to fulfill needs in accord with community and individual norms of sufficiency.

What might be done to improve inclusive local decision-making processes that build awareness, understanding, and evidence of sufficiency principles (see, for example, Princen (2003) and Schäpke and Rauschmayer (2014)) and which actors could do that impact at the meso and macro levels?

What constitutes desirable sufficiency is ultimately a question that societies constantly have to elaborate, guided by available human knowledge. There is also a need for an ongoing process of assessment and adjustment by humanity to navigate toward a safe operating space, both globally and more locally.

Furthermore, platforms for societal development debates/transformative spaces can facilitate and substantiate the foundations of what desirable sufficiency futures entail (Pereira et al. 2018). This includes understanding where there are 'tension lines,' and which interests may be synergized or will continue to go against each other. This includes a broader view of seeing the future as open and not locked in to a certain, unavoidable, development trajectory (as can be found in the idea of 'the end of history' (Fukuyama) as well as in some forms of historical materialism and determinism).

Given the fact that heterogeneity generally increases at higher spatial and social resolution, the question of defining sufficiency appropriately for such a great diversity of contexts and scales remains daunting, if not impossible. In addition, equity principles need to be considered that take into account the relationship between sufficiency of service levels' consumption and their corresponding resource use within planetary boundaries. As argued above, the Pareto efficiency principle should be applied, that is, increasing someone's sufficiency level of consumption should not imply that anybody else's defined sufficiency level is diminished under given planetary boundaries. The Pareto efficiency principle implies that the only remaining malleable variable for sufficiency levels is the efficiency of service provision, if indeed it can be increased above and beyond 'average' prevailing levels.

As a pragmatic solution to this theoretical and analytical conundrum we propose the following consideration. Across different social and spatial scales a minimum level, or 'floor of sufficiency' consumption, as defined by DLS, which is postulated as culturally and social context invariant, is first satisfied (see Box 10 on sufficiency for the Six Transformations). After this

Box 9. Sufficiency levels in energy scenarios.

The sufficiency concept was first introduced by Sachs (1993) and popularized by Princen (2005) in his book on *The Logic of Sufficiency*. Sufficiency levels consider human needs and wellbeing in the broader context of planetary boundaries. The objective is to avoid overshooting the ecological limits of the planet. However, one decade was needed to develop the first energy scenario which explicitly defines sufficiency levels for each dimension of human wellbeing. In fact, the French négaWatt (nW) scenario was developed in 2003. The scenario is based on a bottom-up approach and includes detailed data on sufficiency levels up to 2050. It has been updated regularly with the last update being from 2017 (négaWatt 2017).

The adoption of the Paris Agreement (UNFCCC 2015) is accelerating the development of energy scenarios based on the planetary boundaries. Grubler et al. (2018) developed the first global LED scenario without overshooting the 1.5°C target nor relying on negative emissions technologies while meeting several SDGs. Rao et al. (2019) proposed energy requirements for DLS in India, Brazil, and South Africa. On the other hand, based on lifestyle (LS) changes, efficiency, and limits, Brand et al. (2019) proposed a mobility scenario with low mobility levels for Scotland. More recently Millward-Hopkins et al. (in review) developed the first global scenario explicitly based on the sufficiency concept. The DLS scenario with minimum energy (DLE) (see Box 8) is a bottom-up global scenario which considers the most stringent sufficiency levels identified in the literature (Table 1) (Saheb et al. in preparation).

Table 1. Sufficiency levels considered in 2050 for selected services as identified in scenarios based on the planetary boundaries. Source: Saheb et al. (in preparation).

	Sufficient levels per service required	**Unit**	**Scenarios**				
			nW	LED	DLS	LS	DLE
			France	Global	IND/BRA/ZAF	Scotland	Global
Well-being dimension	Sufficient housing space	m^2/cap	41.9	29	15		15
	Household size	Persons/ household	2.2	Not identified	3		4
	Sufficient space in non-residential buildings*	m^2/cap	15.2	Not identified	Not applicable		Not identified
	Housing thermal comfort (heating)	kWh/m^2/yr	15	21	Not identified	Not applicable	10.4.-12.9.
	Housing thermal comfort (cooling)	kWh/m^2/yr	10				10.14.-14.1.
	Non-residential thermal comfort (heating)	kWh/m^2/yr	37	Not identified	Not applicable		Not identified
	Non-residential thermal comfort (cooling)	kWh/m^2/yr	78				Not identified
	Mobility levels	p-km/cap	15043	9544-17117	10000	9845	4900-15000

*Non-residential buildings include cafes, hotels, restaurants, health, education, leisure, sport, and office buildings including public ones, shopping malls and dormitories

level has been provided, any remaining resource use that would not violate planetary boundaries could in principle be made available to increase sufficiency levels more in line with cultural, social, and regional specific circumstances and (path dependent) variations under some equity (distributional) principle. Planetary boundaries and a normative target for distributional equity (e.g., O'Neill et al. (2018) consider as a desirable social threshold a Gini coefficient lower than 0.3, which is at the high end of the equity of income distributions in countries worldwide) thus would define an 'upper bound' for the resource use of sufficiency levels in service provision and consumption. In turn, behavioral, organizational, and technological innovations could be called upon to maximize service provision levels under these boundary conditions.

Such an approach, albeit in a simplified manner (due to the relatively high level of spatial aggregation as used in state-of-the-art integrated assessment models) was used in the illustrative transformation pathway for an end-use focused strategy toward the SDGs (see Section 3.3 below).

Box 10. Efficiency and sufficiency for achieving the Six TWI2050 Transformations.

The scientific consensus is that the Earth's resoures and carrying capacity are limited. A number of critical tipping points have begun to emerge and amplify the negative impacts of climate-related factors on the livelihood of billions.

Possible strategies for a way out of the ecological crisis include less resource use per unit of service (efficiency), the adoption of ecologically sound technologies (consistency), and the reduction of consumption (sufficiency). The main question being asked is whether well-established consumption habits can be perpetuated or not—and what this means for our economy.

Sufficiency can be defined as 'modifications of production and consumption patterns that help to respect the Earth's ecological boundaries while aspects of consumer benefit change.' This definition of sufficiency is ideologically neutral and does not emphasize either self-deprivation or loss of potential profit or benefit. While this definition puts an emphasis on individual consumer behavior, it incorporates the possibility of political steering and policy. This definition is distinct from efficiency and consistency strategies which aim to provide the same benefit in a more sustainable way. To date, many questions relating to sufficiency have barely been addressed or do not have a final solution. What exactly is sufficiency? Why and in what areas is sufficiency needed? What constribution can it make to sustainable development? And can sufficiency be promoted by political measures which go beyond moral persuasion?

In reality the answer lies in combining efficiency and sufficiency approaches. For example, the move to ride sharing illustrates that complex services, actions, lifestyle choices, or policy measures can seldom be classified as 'only' pertaining to a sufficiency, efficiency, or consistency strategy.

There are two considerations why sufficiency strategies are important building blocks on the path toward sustainbility:

- Efficiency and consistency approaches will often not be enough to limit natural resource consumption to sustainable levels (due to rebound effects, economic growth effects, technological uncertainties, and global development/global justice considerations); and
- Sufficiency approaches can at at times be easier, cheaper, and simpler to accept (e.g., Germany's climate targets can only be achieved if there is a significant increase in the biofuel quota, a doubling (or more) of electricity storage, comprehensive energy refurbishment of buildings, and huge expansion in the use of carbon capture and storage). Systematically taking sufficiency into account could open up more opportunities for action, tap additional potential, circumvent conflicts, and possibly reduce cost.

The potential for triggering a large social transformation toward sustainability includes 'ripple effects' (a measure so compelling that it is likely to be replicated) and the 'potential for structural change' (resulting from a measure changing the individual's situation or social practice in such a way that the benefits are, with high probability, long-term) (see Section 3.2.4).

Questions for further research:

- Beyond energy and climate protection, what are the ecological boundaries and need for action (e.g., in terms of raw material, biodiversity, land, water)? What are the interactions? What risks of problem shifting could occur? This is a question the newly established Earth Commission within the Global Commons Alliance is tasked with answering[a)]
- What combinations of sufficiency-efficiency-consistency strategies are needed?
- What is a suitable policy mix of sufficiency and efficiency instruments, of legal and political feasibility, of distribution effects and of social acceptance?
- What economic impacts of combined sufficiency-efficiency-consistency measures are to be expected?
- How can social transformation be shaped politically? What role do different social stakeholders play in this transformation toward a sustainable culture? (See Chapter 4)

a) www.globalalliance.org

3.3. Cross-cutting strategies: transforming services through a TWI2050 Six Transformation lens

3.3.1. Introduction

How does a demand-side and service-oriented transformation that is at the core of SDG12 relate to the other five TWI2050 transformations (see Chapter 1)? Taking consumption (and resulting production) as the entry point, two major relationships among the Six TWI2050 Transformations become apparent (Figure 20).

First are transformations that are 'enabling' the demand-led transformation of consumption-cum-production systems. Changes in human capacity and demography and digitalization are the two TWI2050 transformations that both support and enable the step changes in efficiency and provision of services as described in the LED scenario (see Sections 3.4.2 and 3.4.3). In turn, transformed consumption/production systems have important spillover effects on the three TWI2050 transformations of decarbonization/energy, food/biosphere/land/water, as well as smart cities, that are 'beneficiaries' of the consumption/production transformation that leads to more equitable access to services while drastically reducing resource use (and

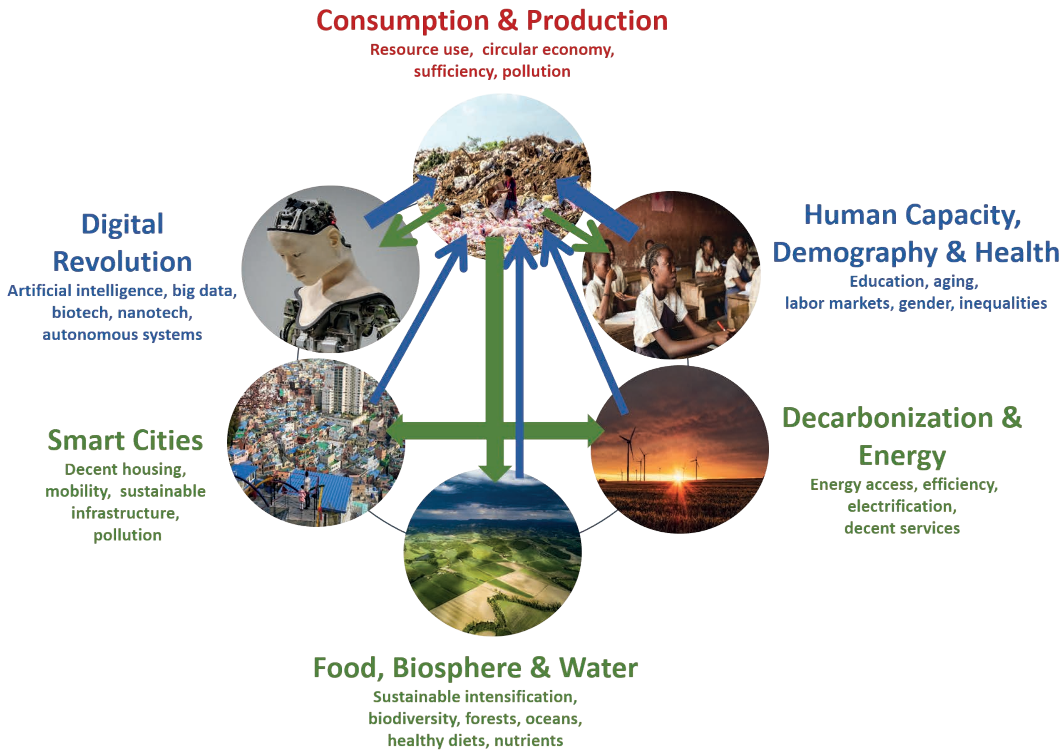

Figure 20. Relationship between the Six TWI2050 Transformations, taking SDG12, Consumption and production, as the entry point. Transformations in consumption/production systems are *enabled* by the SDG-driven changes in Human capacity, demography and health as well as by the Digital Revolution (blue arrows). In turn, cities, energy, food/biosphere/water are *beneficiaries* of the step changes in more equitable service provision with radically reduced resource use (green arrows) to meet SDG12. Second order feedbacks and spillovers augment the interdependence and synergies among all Six Transformations. Graphic courtesy of Arnulf Grubler.

hence costs and environmental impacts) of supply systems of natural resources or of urban infrastructures. While the benefits of the sustainability transformation in consumption/production systems are self-evident (see also the discussion in Section 3.4.4), we need further to discuss the two enabling transformations in the following section: People (actors), their knowledge and behaviors, as well as Digitalization (which was discussed in greater detail in the previous TWI2050, 2019 report).

3.3.2. Enabling transformations to support the SDG12 sustainability transition

3.3.2.1. Population, human capital, and lifestyle change

People are at the center of transformations to achieve the SDGs and long-term sustainability to 2050. While institutions and technologies play a key role in enabling people to practice low-carbon lifestyles, adoption of technologies and new lifestyles require changes in values, attitudes, and subsequently behavior.

Awareness, perception, and concern about sustainable development and climate change are underlying factors that can hinder or facilitate behavioral change because an individual's attitude generally drives the behavior of the person (Ajzen and Fishbein 1980). Indeed, there is evidence that pro-environmental attitudes and climate change concern are associated with the uptake of household behavior such as electricity, water and energy savings, recycling, and purchasing green products (Alcock et al. 2017, Chankrajang and Muttarak 2017). The association between psychological values and behaviors, however, tends to be more related to low-impact behaviors than to high-impact behaviors (e.g., avoiding flying, living car-free, eating a plant-based diet), which require breaking a habit and hence are more difficult to change (Gifford et al. 2011).

Sociocultural and demographic factors are key characteristics in shaping behavior. Not only does consumption and energy use vary with different life stages and socioeconomic status, attitudes and perceptions also fundamentally differ across demographic groups.

Gender differences in climate-relevant attitudes and behaviors are evident across societies. Generally, women are found to be more likely to have better perceptions about the risk of climate change, to be more concerned about climate change, and more likely to embrace sustainable consumption compared to men

(McCright 2010, Gifford and Comeau 2011, Brough et al. 2016). Apart from gender socialization that may explain female value orientations toward the environment (Strapko et al. 2016), having less capacity to cope with and respond to the changing climate make women more vulnerable and more concerned about the impact of climate change. If women are more likely than men to pursue sustainable lifestyles and consumption such as consuming a plant-based diet, producing less waste, and conserving water and electricity (Chankrajang and Muttarak 2017, Rosenfeld 2020), female empowerment (such as through education) that enables women to gain autonomy in decision making may contribute to a reduction in household environmental and resource footprints.

Age is another demographic characteristic that influences climate change attitudes and behaviors. Recent evidence consistently shows that younger people are more likely to believe in human-caused climate change and worry about the problem of global warming and climate change (Reinhart 2018, O'Keefe 2019, Douenne and Fabre 2020). The gradient in climate change concern can indeed be due to the age effect. Because older people have fewer remaining years to live, they may perceive that the severe impact of climate change will not happen in their lifetime. Age disparities in concern about climate change can also be driven by the cohort effect, which results from the unique experience or similar exposure of individuals who were born in the same year. In the case of environmentalism, with younger cohorts being more exposed to media and school curricula related to environmental issues (Howell and Laska 1992), younger generations are generally found to be more environmentally and socially conscious than older generations (Franzen and Meyer 2009).

There is also ample empirical evidence that younger cohorts differ markedly in their consumption patterns, in particular toward 'usership' (of services like urban mobility) rather than 'ownership' of end-use devices and products (such as cars)(see Box 11). For example, only 10% of the people under age 20 in the city of Stockholm now hold driver's licenses, compared to well over 80% for older age cohorts (ITF 2017), a trend that is also apparent across many high-income countries, including the USA (where the percentage of 18-year-olds holding driver's licenses has declined from over 80% to less than 60% over the last 30 years, Sivak and Schoettle (2011)). If more recent cohorts do show greater environmental and climate change concern, replacement of older cohorts with newer ones ('demographic metabolism') can bring about societal change (Ryder 1965, Lutz 2013). Recent global climate movements by young people, for example, may contribute to transformations toward a greener economy as it has been shown that climate change protests have contributed to structural breaks in CO_2 emissions in Europe and Asia (Adedoyin et al. 2020).

Education is another relevant source of heterogeneity in shaping consumption behavior and lifestyle (Figure 21). Consistently, it has been shown that individuals with higher levels of education express higher levels of concern about climate change and are consequently more likely to adopt green behavior (Muttarak and Chankrajang 2015, Chankrajang and Muttarak 2017, Hoffmann and Muttarak 2020). Individuals with higher levels of education tend to have better perception and awareness of climate change risks and better scientific knowledge. This shows that these features are associated with both level of education and the propensity to take pro-environmental actions. An increase in level of education in a population thus can potentially contribute to the adoption of green behavior (Lutz and Striessnig 2015).

Arguably, at the individual level, as income rises with the level of education and consumption increases with income, educational expansion may result in higher emissions due to the adoption of less sustainable lifestyles such as frequent air travel and higher meat consumption. At the macro level, higher educational attainment improves labor productivity and subsequently economic growth (Crespo Cuaresma et al. 2014, Lutz et al. 2019), which in turn lead to higher emissions. Recent evidence, however, points that a rising level of educational attainment only contributes to a modest increase in emissions (O'Neill et al. 2020). Furthermore, because women with higher levels of education have fewer children on average, this would consequently slow down population growth and lower emissions accordingly.

Future consumption patterns and emissions thus depend greatly on population composition. Based on the age-gender-education differentials in climate-relevant behavior described above, we may expect a society with a highly educated population, especially females, to pursue more sustainable lifestyles given their greater concern about climate change, which leads to sustainable consumption and consequently lower emissions (see also Box 12 on more sustainable diets). Therefore, in future socioeconomic development scenarios where investment in education is prioritized, we can expect younger educated cohorts replacing older ones. They can serve as a key force in transformations toward sustainability.

In addition to these demographic factors, changes in preferences and behavior can also be 'nudged' by policies (see Table 2). To change behavior focusing on individual's identities is crucial (NASEM 2019b). Particularly in cases of wide social acceptance of the need to change behavior, such policies can have drastic and rapid effects as demonstrated in the recent

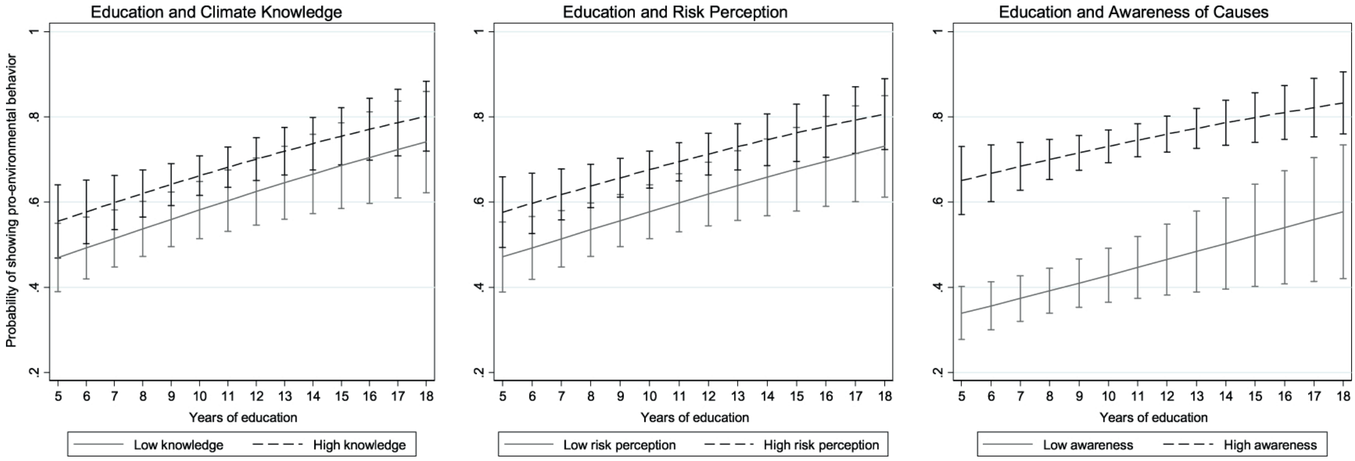

Figure 21. Estimated probabilities to undertake environmental actions for different years of schooling and by knowledge, risk perception, and awareness levels. Source: Hoffmann and Muttarak (2020) CC BY 3.0.

Box 11. Shared urban mobility.

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. Using advanced ICT these mobility service business models (see below) 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 that remain the 'backbone' of urban transport systems).

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 (Figure 22).

	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*

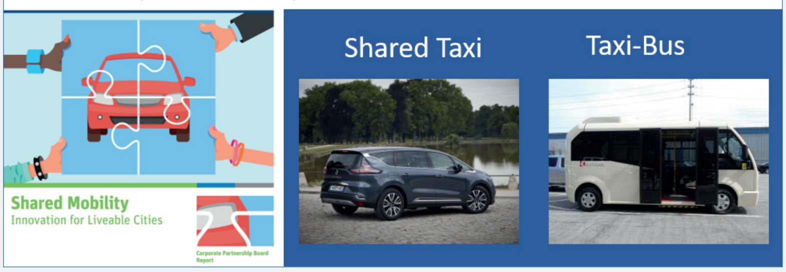

Figure 22. Impact of comprehensive urban shared mobility on vehicle fleets, congestion, mobility costs, and emissions in four example cities, based on detailed big data simulations of trip patterns and an agent-based model of shared mobility coordination. Source: ITF (2019), cfr. TWI2050 (2019), Figure 36.

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 private vehicle use.

Box 12. Charting a consumer-led transition to plant-based diets.

Meat consumption is a major contributor to global warming. Given the worldwide growing demand for meat, and the severe impact of meat production on the planet, reducing animal protein consumption is a matter of food security and public health.

The recently published EAT-Lancet report *Food in the Anthropocene* (2019) warns that unless red meat consumption is significantly reduced, it will be impossible to feed, in a healthy and sustainable manner, an estimated global population of 10 billion people by 2050. Meat-based diets are the norm in Western societies, with vegetarians accounting for less than 5% of the population. Rationalization of meat consumption in the West is summarized in the 4Ns: meat is natural, normal, necessary, and nice.

Changing consumer food behavior is a challenge and requires a positive attitude based on reasons and motivations. Fear-based appeals can backfire and lead to a decrease in people's willingness to reduce their carbon footprints. Taste preferences, culinary traditions, and social norms factor into food choices. Historically, animal welfare and health have been the two main motivations for people in developed countries to become vegan or vegetarian.

Studies carried out by the European Commission show that only a small minority of people are aware of the meat impact on the planet, are willing to stop or significantly reduce meat consumption for environmental reasons, and have already changed their food choices for ecological reasons.

The majority of consumers underestimate or ignore the potential of reducing meat consumption to mitigate climate change. As long as consumers perceive food as detached from the environment, it will be hard for them to make sense of the fact that food has an environmental impact. This may help explain why sustainability messages in favor of meat reduction are difficult for consumers to understand. A second barrier is that consumers have an overall positive image of meat that eclipses the value of environmental protection and climate mitigation.

However, environmental motives are gathering increasing appeal with significant proportions of Western consumers ready to adopt certain meat reduction strategies, like meat-free days. Given that dietary habits are not static, providing consumers with nutritional and culinary education and information on the environmental toll of meat production could be a promising strategy to increase awareness and willingness. Those who are limiting meat consumption are typically female, young, meat-reducers ('flexitarians'), ecology-oriented, and more likely to live in Europe and Asia than in the USA.

COVID-19 crisis. Radical changes in social organization and rhythms in the form of home schooling, home office, wearing facial masks in cultures where these have not been usual in the past, etc., have been implemented quickly and become a new social norm. Evidently the shared commitment to respond to an exceptional crisis has resulted in these drastic behavioral changes that underlie the success of the crisis response of social distancing. They are also evidenced by quantitative indicators of resource consumption (see Box 11).

3.3.2.2. Digitalization

Digitalization is the general purpose (GP) technology of the 21st century. A GP technology is one that is applicable across a wide set of applications, sectors, and countries and that has the potential to alter ways of functioning and use of other technologies, thus creating new industries, businesses, and novel applications. Historical examples of GP technologies include steam power in the 19th century, and electricity in the 20th.

For the consumption/production nexus, digitalization has three principal positive impacts that 'enable' the transformation to more sustainable consumption and production systems. Digitalization enables:

- Expansion of services at near-zero marginal costs of transactions. This vastly reduces costs of digitally enabled service provision in the domains of communication, entertainment, financial transactions, education, or health care and hence increases affordability of these services to poorer segments of society.
- Matching demand and supply in real time through digital coordination platforms and 'smart' control systems offer vast potentials for better asset utilization, improved quality of service, and resource efficiency, e.g., in the domains of the sharing and circular economy or of 'smart' cities, homes, and businesses.
- Substituting analog, physical service provision modes (e.g., physical media like newspapers, CDs, etc.) via virtual, digital (online and streaming) platforms, or of traditional physical forms of communication (e.g., business travel) by digital, 'dematerialized' forms of communication (tele-working, -collaboration, -conferencing).

The general principles and multitude of potential applications of harnessing the Digital Revolution for the benefit of sustainable development were discussed in detail in the TWI2050 (2019) report on the Digital Revolution. Here we provide some illustrations of potential benefits, particularly relevant for transforming prevailing consumption and production systems including new forms of organization and business models, digital device convergence, as well as health systems, considering in particular the first lessons from the COVID-19 crisis. We end with a cautionary note that digitalization may not only lead

Table 2. Five levers to change consumer behavior towards sustainability. Source: adapted from White et al, (2019) and UNEP (2019).

Lever	Action Steps	Examples
Use social influence	Link the desired behavior to relevant social norms, appealing to human desire to fit in.	Calgary's successful grasscycling initiative to reduce drop-offs at landfills: "Your neighbors are grasscycling. You can too!".
	Show that others are engaging in the behavior.	Telling students that other commuters were ditching their cars in favor of cycling. Reducing food waste by telling buffet diners that they could return for refills. Highlighting a product's positively viewed attributes more than its *green* credentials (Tesla is spotlighting innovative design and functional performance over environmental benefits.)
	Make sustainable behavior public.	After Halifax residents were required to put household waste in clear bags for pickup, garbage going to landfills decreased by 30%.
	Create positive associations with the behavior.	Asking hotel guests to signal their participation in energy conservation by reusing towels. Campaign to promote solar home panels became more effective after advocates explained why they had installed the panels at their own homes.
	Foster healthy competition between social groups.	WWF's Earth Hour competition to switch off lights has expanded to cities in 188 countries.
Shape good habits	Make sustainable behavior the default.	Using 16 billion disposable coffee cups as the default option in an effort to cut back on the 500 billion plastic cups used annually; energy-saving temperature setting in residential buildings as default setting; providing free travel cards for public transport.
	Use prompts and feedback to create positive habits.	Text messages reminding people to use eco-friendly commute options. Utility bills showing how a household's energy or water usage compared to their neighbors.
	Use incentives appropriately – and with care.	Coca Cola's initiative to install reverse vending machines to reward recycling of plastic bottles.
	Introduce sustainable behaviors during major life changes.	Encouraging people to adopt eco-friendly behaviors (after moving, taking a new job, marriage).
Leverage the domino effect	Make the first sustainable action particularly effortful.	IEKA's switch to sell only LED light bubs had a snowball effect on consumer behavior (lowering thermostat, insulating doors, wearing warmer clothes…)
	Encourage meaningful commitments to behavior change.	Avoid publicizing actions that require only small commitments. Making behavior change last is difficult.
	Don't allow consumers to signal that they are 'good people' with an initial token act.	Risk of slacktivism and negative spillovers (e.g., driving more after buying a fuel-efficient car).
Decide whether to talk to the heart or the brain	Tap into feelings of hope and pride.	Bacardì & Lonely Whale teaming up to remove 1 billion single-use plastic straws by 2020.
	Subtly activate moderate feelings of guilt.	*Explicit* guilt appeals create negative reaction. Unilever's campaign to spotlight its sustainability farmed palm oil, even while acknowledging that it leads to rain forest destruction elsewhere ("what you buy at the supermarket can change world…small actions, big difference").
	Frame messages in terms of what can be lost.	Labels indicating the "10-year dollar energy cost savings" are prompting more energy-efficient purchases.
	Offer concrete information and reference local impacts.	New York City's campaign: garbage thrown out one day can fill the Empire State Building. Washing your clothes in cold water for one year equals a lifetime cell phone charging costs (Tide).
Encourage experiences over ownership	Consider business models that offer experiences rather than material goods.	Tinggly's tagline to "Give stories, not stuff" to bypass conventional presents.
	Think about how to repurpose your products when the consumer is finished with them.	"Rent the Runway" to share used clothing; Lyft's promise to carbon offset rides globally. Eileen Fisher and Patagonia offering to buy back, refurbish, and resell clothes form its customers.

Box 13. Evidence of demand response dimensions to shocks based on COVID-19 pandemic mitigation.

The ongoing COVID-19 crisis has demonstrated that human behavior can change quickly provided that suitable technologies are available. The lifestyle response to lockdown and social distancing measures has been drastic and has shown the large malleability of human behavior and demand for certain goods and services, at least in the short run. Which changes will stick around for longer, however, remains uncertain.

We have seen abrupt shifts to telework and home schooling, the closure of recreational places, the reduction of production capacities due to decreasing demand or disruptions in supply chains, and large shares of the population (temporarily) out of work. As a consequence, service demand reductions compared to the same period in the previous year have been reported for the lockdown period. Reductions have been most striking in electricity consumption (e.g., a drop of daily electricity consumption by 15%–20% in the Russian Federation, between 25% and 40% in Western Europe, and 20%–25% in China (Bruegel 2020), while largely fluctuating between +5% and -15% in Nigeria) and transport activity (e.g., urban mobility was down to 4%–15% of normal levels in cities such as Amsterdam, Barcelona, Los Angeles, and Sao Paolo (Gosh 2020); in Vienna half of the population no longer commuted to work during the lockdown (Google 2020); car traffic saw a reduction of congestion levels by up to 90% across European capitals (Dickson 2020); and air traffic was down close to 90% in Europe (EUROCONTROL 2020)).

Digitalization has enabled many of these behavioral changes: 1.5 billion children were out of school in 175 countries as of mid-April, 180 million schoolchildren were in home schooling in China (Iqba et al. 2020). Without digital technologies, a switch to home schooling would have been unthinkable. Differences in access to digital technologies (and even electricity) known as the 'digital divide' deepen societal disparities and have long-term negative impacts for those who currently do not benefit from such technologies (Patrinos and Shmis 2020). The crisis has exposed the extent of the digital divide in education and health by revealing the limits of connectivity, which endangers public health as well as education. This should lead governments to take more vigorous steps to extend broadband service and eventually 5G to all citizens as a matter of national security. A paradigm shift in education could also reduce the cost of education and democratize access to higher education. New innovations to increase sustained digital engagements and interactivity with educational materials will likely be required.

For those lucky enough not to have lost their jobs and who can work from home, a pervasive adoption of teleconferencing and e-meetings (e.g., +200% in daily meeting minutes to reach close to 3 billion minutes per day on Microsoft Teams in April 2020 (TechRepublic 2020)) has occurred. Despite the surge in speaking minutes on the phone (+100%) and internet traffic (+20%–25%) (Kang 2020), no bottleneck in communication infrastructure was noticed, for example in Europe. This could lead to a paradigm shift in the future of work; a permanent change that will reduce costs and movement of people. Many services do not require in-person contact, including medicine, legal services, etc. This would affect demands for office space in downtown areas. Holding meetings online has become the norm, which could lead to reduced travel activity.

The lockdown has also led to increases in e-commerce and online purchases, with all their environmental and economic impacts. Amazon, for example, hired more than 175,000 new staff during the crisis to deal with the increase in orders (Palmer 2020). At the same time, international trade has seen a plunge. The tourism sector has been hit especially hard, including its most polluting services of cruises and air travel, which basically came to a halt with travel restrictions in place.

Positive environmental effects of the changes in human demand and activity have been reported from around the world: reduced air pollution in many cities (e.g., China (Kottasová 2020), northern Italy and the Federal Democratic Republic of Nepal (McGrath 2020)), the comeback of wildlife on land and in the sea (Gardner 2020), brighter night skies, or lower GHG emissions (McGrath 2020).

It is unclear which of these recent drastic changes in behavior will have long-lasting impacts on lifestyles and social forms of organization. Rebound effects in energy demand and economic activity, as have been experienced in previous crises (Peters 2020), are likely. Yet, the impacts of pervasive use of digital services are likely to last. The digital transformation with every citizen having access to smartphone connectivity to government should lead to two-way connections, especially in a pandemic or other crises, allowing the government to provide information to citizens (with increased targeting to neighborhoods, etc.) and for citizens to provide information to the government about immediate needs and developments.

Many companies that have resisted telework for years are now dealing with hundreds or thousands of employees in home offices and have realized that the world has not come to a halt. Twitter, for example, announced that all employees can now work from home forever (Paul 2020). This poses new questions on the impact on salaries or a new wave of outsourcing, but will undoubtedly have an impact on mobility demand.

New business opportunities have been created (e.g., online theaters and therapy). Sectors that have long fought digitalization have quickly adapted and have shown to be innovative in responding to changing circumstances (e.g., e-medication, prescription, and treatment in the Republic of Austria). Digitization of health care is likely to be pushed forward considerably, which could increase access and reduce costs of medical care (see Chapter 2). Necessity has already led to a great increase in telemedicine as both a means of consultation on symptoms of potentially infected patients without hospital visits and to reduce the burden on doctors and nurses while better protecting them from contagion. In the long run, telemedicine, whenever possible, may become desirable and far more efficient for both patients and doctors. In addition, with more sensors available through smartphones and smartwatches capable of providing real-time data to medical providers, preventive care may be substantially improved, and costs further reduced.

Widespread adoption of such practices and innovations can have lasting impacts on service demand and behavior. It is to be seen how these changes play out in the long run.

Table 3. Examples of New Service provision and business models in the digital, service, and sharing economies.

Model	Description	Company Example
Freemium	Applicable for products and services with low marginal costs or where marketing and customer information have higher value than operating costs	Spotify, Linkedin, Xing
Subscription	Aim is to bind the customer long-term. Customer benefits from improvements and extensions of the service.	Amazon, Netflix
Free offerings	High value generated through customer information	Google, Facebook
Marketplace model	Digital marketplace connecting sellers and buyers	Amazon, Uber, Alibaba, eBay
Sharing economy	Access-over-ownership model, renting and leasing.	AirBnb, Sharoo, Mobility
User experience premium	Service, the brand and especially the experience of the customer are improved and premium prices are charged	Tesla, Apply
Pyramid model	With easy billing by technical aids, the pyramid models can be quickly built up and easily managed. Suitable for products with high margins and which can be easily explained.	Amazon, Microsoft
Ecosystem	To bind customers to an ecosystem in the long term through a 'lock-in' process in a service	Apple, Google
On-demand model	The immediate access is sold. The delivery, the product or the service can be called up at a certain point in time.	Amazon prime, Upwork, Uber

to resource conservation, but through the possibility of new services also lead to an increase in resource use and consumption, which requires continued monitoring and technology and market foresight.

Digitally enabled business models have introduced new service and production opportunities for many consumers. Advances in research are holding promise for new frontiers of discovery. At the same time, the accumulation of personal data among governments and companies is raising concerns about privacy, digital control, and anti-competitive dynamics which require continued monitoring and ultimately regulatory oversight and regulation.

Table 3 summarizes a range of service provision and business models in the digital, service, and sharing economies with corresponding examples.

Resource conservation through digitalization of services and device convergence is another illustration of the powerful leverage effects of digitalization on SDG12. Figure 23 contrasts the traditional 'analog' model of service provision in which consumers own a wide range of specialized, dedicated devices each delivering a specialized service with the new model of 'digital convergence' in which all services are delivered in digital form via an integrated delivery platform (consumer interface): the smartphone. This alternative model of service delivery enables step changes in materials conservation and efficiency: material use (weight) is reduced by a factor of 260, embodied energy by a factor of 23, operational energy by a factor of 30, and peak power needs by a factor of 90. Even if such digital device convergence should not become 100% complete, such vast resource conservation potentials will nonetheless translate into sizable reductions in materials and energy use of consumer appliances.

New services leading to resource demand increases

Human ingenuity and perceived needs will drive the supply and demand for new services, some of which may counteract, or 'take back' efficiency improvements. Let us look at just one example: watching YouTube videos on a mobile phone. Preist et al. (2019) provide a detailed analysis of the energy and CO2 emissions from watching YouTube videos. Figure 24 shows that YouTube servers themselves only consumed 353 GWh per year,[3] whereas the use of core and metro networks (1,850 GWh per year), access networks (4,418 GWh per year), user devices (6,091 GWh per year), and especially cellular networks (8,507 GWh per year) are using many times more energy to watch those YouTube videos. And yet, combined YouTube's electricity use is (with some 21,220 GWh) only less than 0.08% of global electricity consumption. Streaming a video on a mobile phone is, however, more energy consuming than watching it on a LAN-connected computer, especially close to a backbone network. In fact, moving to the next-generation 5G mobile networks[4] is expected to greatly increase the energy and climate footprint of online video streaming, due to the much higher bandwidth available.

An even higher impact could be new video gaming streaming. According to New Scientist Magazine, Google launched its Stadia streaming service which

3 According to some estimates, 10 MtCO2 emissions are due to YouTube servers alone.

4 which are currently rolled out only in China and the Republic of Korea.

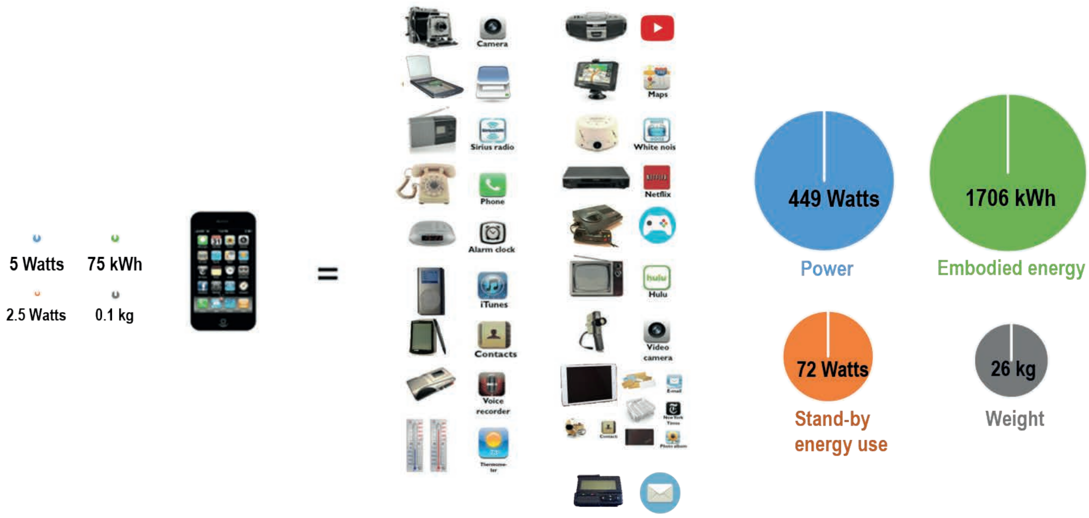

Figure 23. The rapid progress of information and telecommunication technologies could be an indication of the path-breaking potential of next-generation digital technologies and their clustering in new activities and associated behaviors. A smartphone needs between 2.2 Watts in standby to some 5 Watts 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: based on data in Grubler et al. (2018) and visualization of Tupy (2012), Graphic courtsey of Nuno Bento, cfr. TWI2050 (2019), Figure 20.

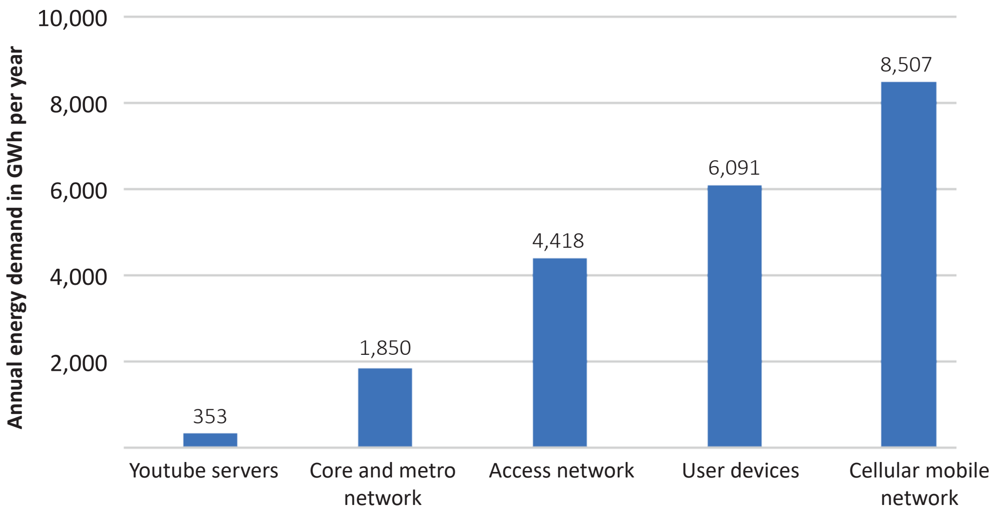

Figure 24. Estimated energy usage of YouTube services across the entire provisioning chain. Source: Roehrl (2019), based on data reported in Preist et al. (2019).

allows video gaming with a Wi-Fi controller, instead of a computer or a game console. Due to the streaming, and especially if this will be streamed on mobile phone networks, this new service like many others that are being planned are poised to greatly increase energy use and GHG emissions.

These illustrative examples have highlighted both the upsides and downsides of digitalization: creating vast opportunities for improved energy and resource efficiency on the one hand, but potentially also novel services or vast demand increases for existing services that may counteract, or 'take back' some, or a significant part of efficiency improvements on the other. Future technological innovations, new behaviors, and re-definition of what constitutes 'desirable' of 'sufficient' in terms of service demands remain wide open and uncertain. A prudent 'precautionary' strategy therefore suggests aiming for the maximum improvements in resource efficiency possible, to make room for these future contingencies while remaining safely within planetary boundaries.

3.4. How big is the efficiency resource?

3.4.1. Efficiency of service provision

The core concept and key intermediary between natural resources and human wellbeing of this chapter is that of services and service provision systems. The service concept recognizes that the traditional economic conceptualization of 'demand' as bundles of goods (fuels, material goods, etc.) exchanged with consumers via market transactions (gasoline for operating a car, grain for producing food, a cell phone to communicate, etc.), are in fact intermediary, economic rather than 'final', social demands. The more appropriate unit of 'demand' is rather the services (mobility, nutrition, communication, etc.) that the use of economic goods enable to further human wellbeing. Service-provisioning systems are (alternative) combinations of products, end-use devices (technologies) and forms of (market) organization that provide particular services. For example, the service of personal mobility (passenger-km traveled) can be provided alternatively by electric or gasoline powered privately owned vehicles, but also by shared vehicles, or by soft-mobility modes (walking and cycling), or by means of public transport (electric metros, or diesel buses). Services can contribute directly to human wellbeing (shelter, comfort, nutrition) or are themselves intermediary (e.g., goods transport, ton-kms), that is, are required 'upstream' in the form of materials and infrastructures for the provision of direct services.

Service-provisioning systems to satisfy service needs (e.g., illumination, nutrition, thermal comfort, etc.) comprise a series of interlinked processes to convert primary resources (e.g., coal, minerals) into usable products (e.g., electricity, copper wires, lamps, light bulbs) (see Figure 14 above). It is useful to differentiate between conversion and processing steps 'upstream' of end-users (mines, power plants, manufacturing facilities) and 'downstream', that is, those associated with end-users, including service levels, and wellbeing benefits (Kalt et al. 2019). The efficiency by which natural resources are extracted, converted, processed, delivered, and used for the provision of services can be calculated by the compound efficiency of all interlinked steps in the service provision chain.

Illustrative examples of such resource processing systems steps and associated conversion losses drawn from the literature are shown in Figure 25 for energy (direct energy conversion efficiencies (Nakicenovic et al. 1993, De Stercke 2014)), water use in food production systems (water use efficiency and embodied water losses in food production, processing, and consumption (Lundqvist et al., 2008; Sadras et al., 2011)), and materials (Ayres and Simonis 1994, Fischer-Kowalski et al. 2011) using the example of steel manufacturing, use and recycling at the global level (Allwood and Cullen 2012).

Invariably, conversion losses along the entire service provision systems are substantial, ranging from 83% (water) to 86% (energy) and 87% (steel) of primary resource inputs. In other words, only between 14% to 17% of the harnessed primary resources remain at the level of ultimate service delivered, the remainder being lost in upstream conversion steps and dissipated to the environment. Conversely, given these low aggregate systems efficiencies, the primary resource inputs for service provision are substantial. With a compound systems efficiency of 14%–17%, each unit of service delivered requires between 7.1 (1/0.14) to 5.9 units (1/0.17) of primary resources to be extracted as input to the corresponding service provision chain.

A substantial part of these losses happens at the level of end-use in final service delivery (where losses account for 47%–60% of aggregate systems losses for steel and energy respectively, and 23% in the case of water embodied in food, that is, in food waste). The efficiency of service delivery (for a detailed discussion see Brand-Correa and Steinberger (2017)) has usually both a technological component (efficiency of end-use devices such as cars, light bulbs) and a behavioral component (i.e., how efficiently end-use devices are used, e.g., load factors). Using the example of mobility where service levels are usually expressed by passenger-km, the compound service provision efficiency is thus a function of the fuel efficiency of the vehicle and its drivetrain (typically only about 20%–25% for internal combustion engines, but close to 100% for electric motors) plus how many passengers the vehicle actually transports (load factor, typically as low as 20%–25%, i.e., one passenger per vehicle that could seat 4–5), that is, an aggregate end-use and service delivery efficiency of between 4% (0.2x0.2) to 6% (0.25x0.25) only. Below we discuss in more detail the exemplary resource efficiency of three service-provisioning systems: energy, water embodied in food, and materials using the example of steel.

The aggregate efficiency of service provision from energy inputs is estimated globally to be 14% (Figure 25, panel a). Estimates by different service categories/sectors are also available in the literature (see Figure 25, panel a) which suggests that the lowest compound efficiencies are for transport services, followed by residential/commercial applications (thermal comfort, lighting, communication), and materials (industry). The largest losses occur in the provision of energy services at the point of end-use: conversion of final energy to useful energy (chemical energy of gasoline to kinetic energy at the drivetrain; conversion of heating fuels to heat, or of electricity to lumens of light) and in the conversion of useful energy to energy services (service efficiency, e.g., load

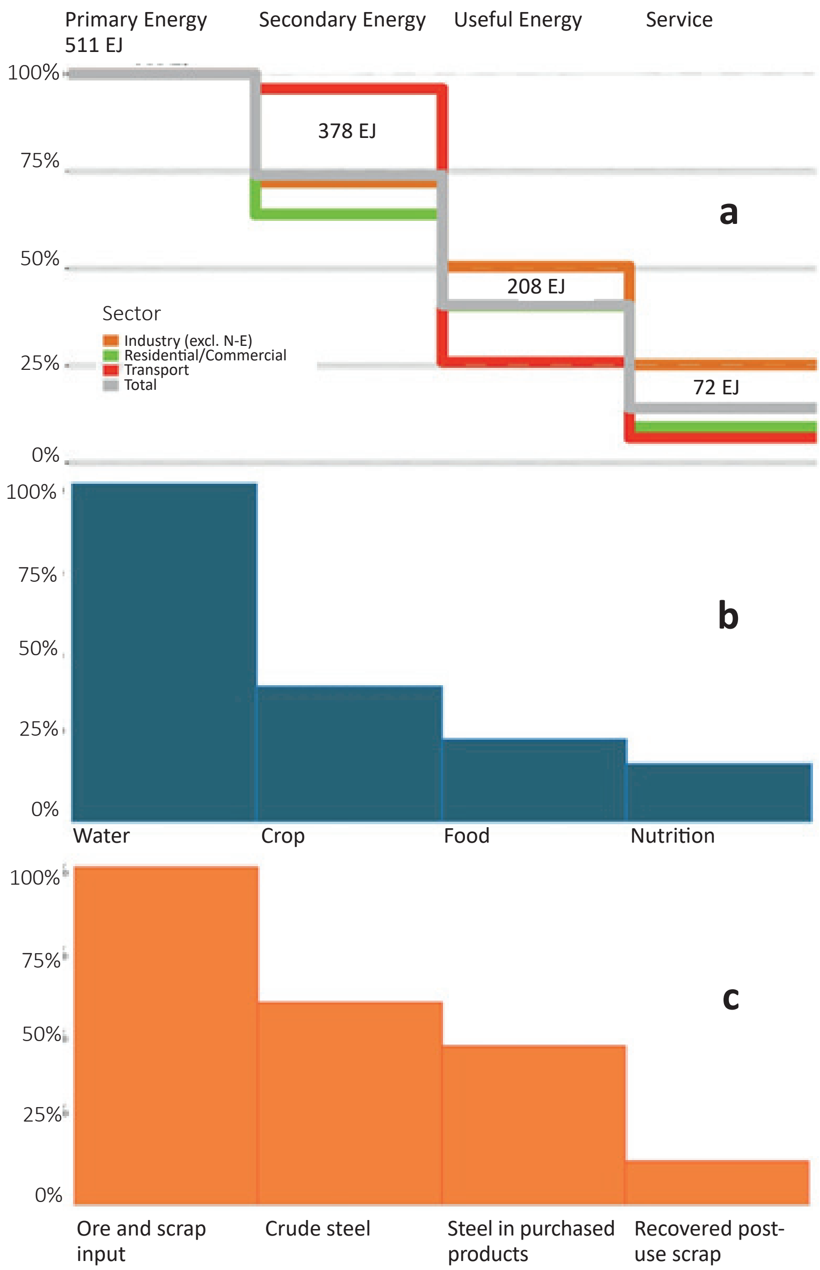

Figure 25. Efficiency cascades of resource use for energy (top panel a), aggregate, and efficiency by main consuming sector, water embodied in food (middle panel b), and materials using the example of steel (bottom panel c). The percent of the original primary resource extracted remaining at each respective conversion step until service delivery is shown as a percentage. Source: First-order estimates based on Lundqvist et al. (2008) and Sadras et al. (2011). Panel c (bottom) materials efficiency shown for the example of steel from primary raw material inputs (iron ore and steel scrap) to final retail, and recovery of post-use steel (scrap). The difference to primary inputs is comprised of additions to the material stock in the form of buildings and infrastructures but also due to material losses, part of which may be recoverable in future. Source: updated with 2016 data (J. Cullen pers. comm.) from Allwood and Cullen (2012); Ayres and Simonis (1994), Fischer-Kowalski et al. (2011). Graphic courtesy of Arnulf Grubler and Benigna Boza-Kiss, cfr. TWI2050 (2018), Figure 2.24.

factors of vehicles, thermal losses in buildings without insulation, etc.). Conversely, efficiency at the supply-side (primary to final energy) are comparatively modest, with the largest conversion losses associated with the generation of electricity, which are, however, largely compensated by higher end-use efficiencies of electric applications (e.g., vehicles) illustrating the importance of always considering service-provisioning systems holistically and along the entire resource extraction-service delivery chain.

The example of energy efficiency in service provision discussed above also illustrates the contrast of the simple method of compound output/input resource efficiency at its calculated aggregate efficiency (14%) with alternative, more sophisticated methodologies to determine resource use efficiency that also take qualitative characteristics into account: the so-called exergy method (see Nakicenovic et al. (1996), Sousa et al. (2017), Grubler et al. (2012a)). Illustrative exergy efficiencies of entire national or global service provision systems range from 2.5% (USA, Ayres (1989)) to 5% (OECD average, Grubler et al. (2012a) and 10% (global, Nakićenović et al. (1996)) respectively. Indicative potentials for improvements revealed by exergy analysis thus range from a factor 10 to 20 with the highest improvement potentials at the end-user and service-provisioning levels. This suggests that improvement potentials of a factor 6–7 based on direct conversion efficiencies are in fact rather conservative and could at least be doubled again.

A comparable efficiency cascade for water (Figure 25, panel b) based on irrigation water embodied in global food production and consumption, yields a comparable conclusion. While the global irrigation water use efficiency of some 40% (Sadras et al. 2011) is relatively modest, losses at the end-use part of the food chain, estimated at 43% efficiency (Lundqvist et al. 2008), are equally high, yielding an aggregated embodied water for food systems efficiency (from farm to plate) of 17%. While improved technology can help the efficiency of irrigation (effective water uptake by crops) somewhat, it needs to be noted that irrigation-associated water losses do not 'disappear.' Instead they are available for ecosystems services and recycling by the global hydrological cycle. Losses of water embodied in food are more consequential and also associated with corresponding unnecessary ecological footprints (land use) and economic impacts. These losses in water embodied in farm products arise from conversion losses in animal protein production, food losses in retail and distribution, and—above all—in food waste at end-use consumers, estimated to amount to up to 30% in industrialized countries (Gustafsson et al. 2011). Minimization of food wastes as well as dietary shifts away from high levels of red meat consumption, that has a particularly unfavorable calorific conversion efficiency (grain food calories needed per meat calorie delivered), are thus important strategies that synergistically link SDG2, SDG15 and SDG6, but they all entail changes in human behavior and habits, thus requiring social change rather than technological change alone (NRC 2015, NASEM 2019b).

The case of steel (Figure 25, panel c) further supports the conclusions of significant resource efficiency losses and improvement potentials. Globally only 47% of all primary iron and steel scrap end up as steel in purchased products (Allwood and Cullen 2012) and only 13% of primary material inputs come from re-utilized post-use steel scrap (Allwood and Cullen 2012).[5] Particularly, the material losses in the upstream supply chain of steel (manufacturing) deserve attention, but also face quality challenges, especially for high-quality and specialty steels. Not unlike the case of energy, where exergy (the ability of energy to perform useful tasks) gets destroyed, even if energy is conserved, important quality characteristics of steel can be lost even if the scrap tonnage may be recycled. Increasing recycling rates for materials also faces a trade-off with the desirability of lifetime extensions of products (buildings, vehicles, etc.) as a material efficiency strategy. Minimizing materials use beforehand through design changes (lightweighting) or alternative service provision models (e.g., shared vehicles fleets with high load factors and fewer vehicles instead of large numbers of individual vehicles that are used only rarely (typically only one hour a day), also linked with the notion of sufficiency (see Section 3.2.4)) are further options.

To harness additional gains in efficiency by shifting the focus in service provision systems to the end-user can translate into large 'upstream' resource reductions. For each unit of improvement at the end-use point of the service provision system, primary resource inputs are reduced between a factor of 6 to 7 units (water, steel, energy). For example, reducing energy needs for final service delivery equivalent to 1 EJ, reduces primary energy needs by some 7 EJ. This is hence a significant leverage point to waste less, while maintaining or improving services.

More efficient systems tend to be more resilient as they are more flexible in how to meet service demands as the overall system is smaller. In that they are not as prone to external shocks.

3.4.2. Harnessed efficiency potentials by 2050

How much of these vast efficiency improvement potentials discussed in the previous section can be realized? Figure 26 illustrates the realizable efficiency improvement potentials by 2050 in comparison to 2020 (see Figure 25 above for comparison and conceptual definitions) decomposed by region and also by type of end-use using a (highly ambitious) LED scenario (Grubler et al. 2018) as an example.

The aggregate efficiency from primary energy to ultimate service delivery improves from 14% in 2020 to 41% in 2050, equivalent to 334 EJ, that is, two thirds (66%) of 2020 primary energy use. Efficiency improvements are largest at the end-user stage: -153 EJ in service delivery (e.g., higher service delivery

5 Data for global steel production in 2016, updating (Jonathan Cullen, pers. comm.) Allwood, J. and J. Cullen (2012). *Sustainable Materials with Both Eyes Open. Future Buildings, Vehicles, Products and Equipment- Made Efficiently and Made with Less New Material.* Cambridge, UIT Cambridge Ltd.

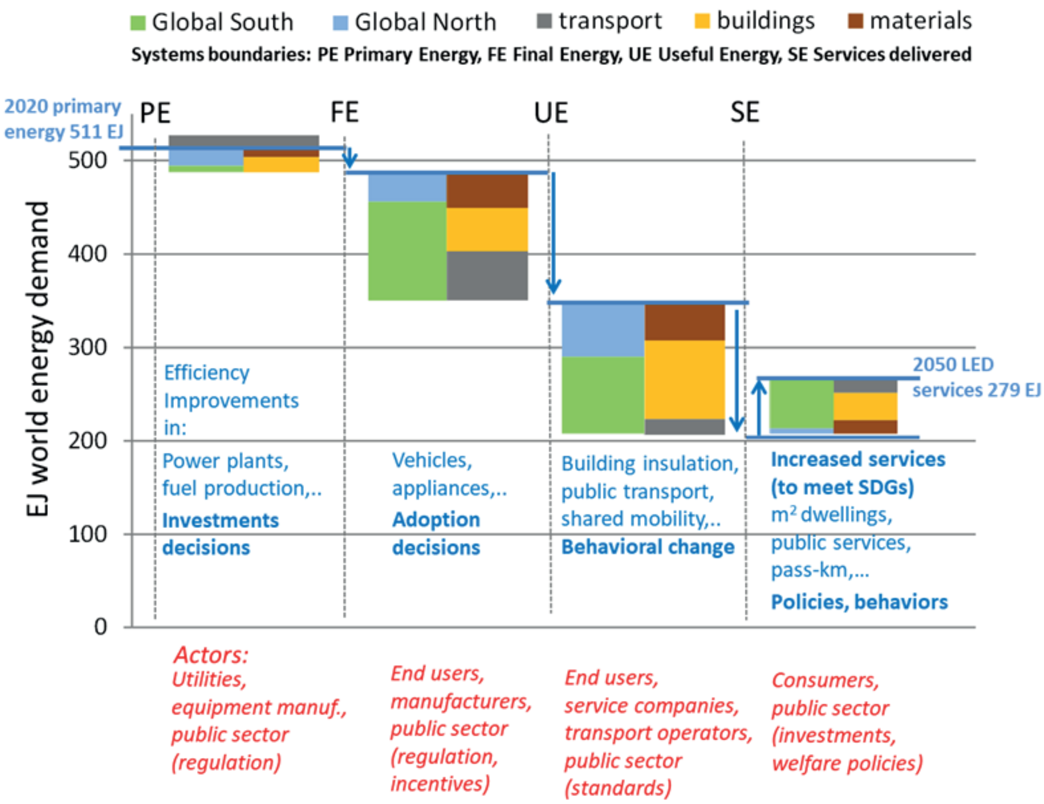

Figure 26. Realized efficiency improvements in an ambitious Low Energy Demand (LED) scenario compared to 2020 base year (in EJ). Efficiency-induced reduction in energy use are shown at each corresponding stage of the service provision chain and are disaggregated by global macro-region (North, South) and by type of service/sector (buildings, transport, materials). Also shown are increases in energy use to meet SDG objectives like DLS for all, as well as systems effects of transport electrification that improve the efficiency in end-use but entail additional conversion losses in electricity generation upstream (gray bars on top of 2020 primary energy). Source: derived from data in Grubler et al. (2018). Graphic courtesy of Arnulf Grubler.

efficiencies via more public transport and shared mobility, more efficient buildings, dematerialization via digital service provision, etc.) and -134 EJ in end-use energy conversion (more efficient [e.g. electric] vehicles, appliances, etc.), whereas efficiency improvements in energy supply are comparatively modest (-23 EJ—without systems interdependencies). By type of use, efficiency gains are the largest for buildings (including appliances): -160 EJ (pervasive adoption of *Passivhaus* building designs), followed by materials with -100 EJ (dematerialization via digitalization and shared mobility and recycling), and mobility with -50 EJ (more public transport, shared mobility, and electrification of vehicles). These efficiency gains are countered by activity increases and the impacts of system interdependencies. Realized efficiency improvements are therefore somewhat lower than suggested by the simple comparison to 2020 (334 EJ). Systems interdependencies (e.g., more efficient electric vehicles improve efficiency at end-use conversion, but lower the efficiency of energy supply (more conversion losses at power plants)), as well as substantial increases in service levels to meet the twin objectives of development in the Global South and DLS for all, 'take back' some of the energy savings. Primary energy demand in the LED scenario by 2050 is, however, with 279 EJ still 45% (-232) lower than in 2020 (511 EJ).

3.4.3. SDG benefits of demand-side solutions

Figure 27 contrasts a demand-side transformation strategy (using as example the LED scenario, Grubler et al. (2018)) with more conventional supply-side strategies that aim primarily at limiting global warming to below 1.5°C, as well as their corresponding (no climate policy) baselines for six illustrative SDGs and associated quantitative indicators.

The demand-side, service-oriented efficiency strategy of LED generally outperforms other scenarios in all six SDG indicators examined in Figure 27. The LED scenario scores high on the social goals-oriented SDG indicators (SDG2, SDG3, SDG7) due to its approach of maximizing useful service delivery with minimal resource inputs and its normative scenario feature of providing at least Decent Standards of Living for all while also allowing regional variation in culturally

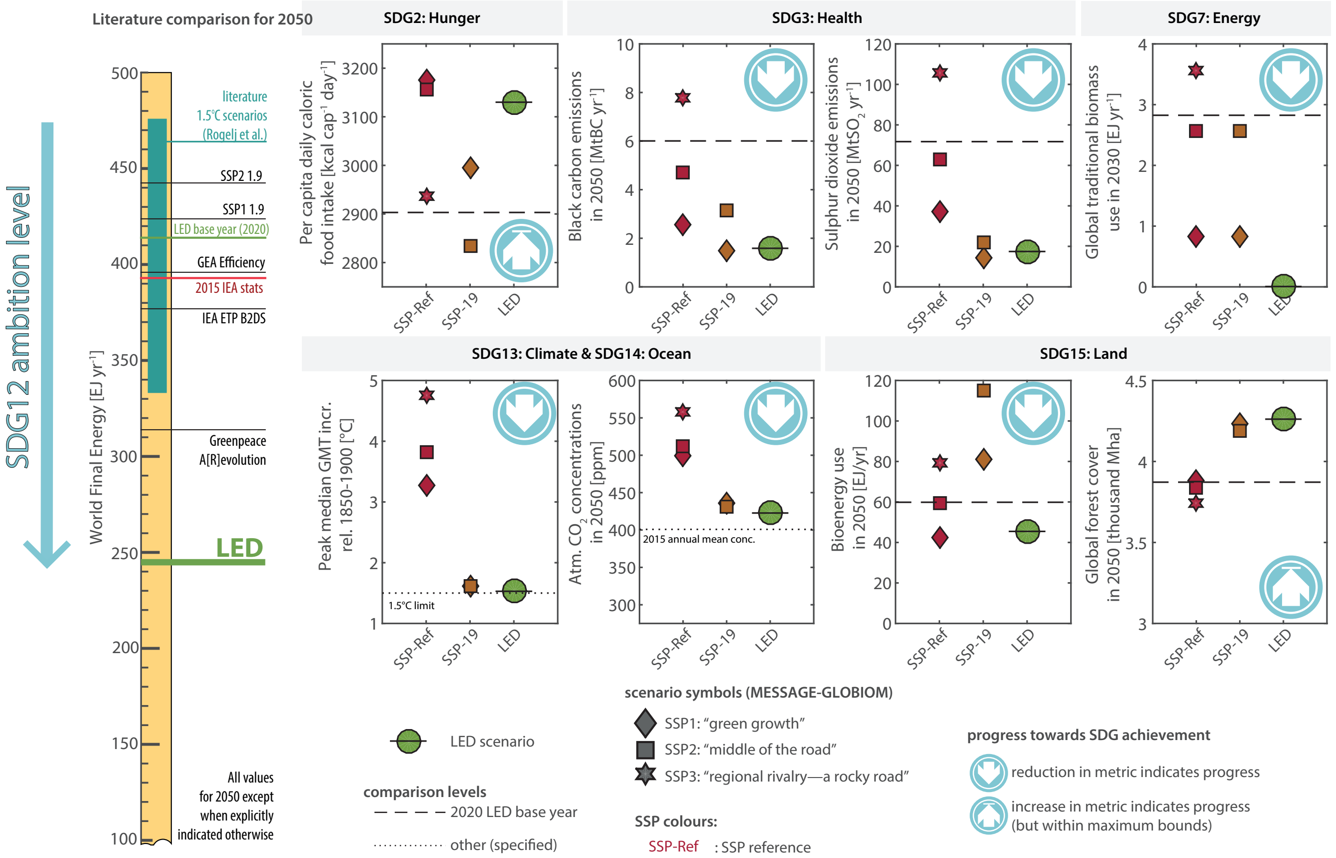

Figure 27. Scenario comparison of SDG synergies and co-benefits of a demand-side focused (SDG12) versus supply-side focused scenarios for meeting a 1.5°C climate target (SDG13). Also shows desirable direction for various SDG indicators. Source: After Grubler et al. (2018), cfr. TWI2050 (2018), Figure 3.7.

framed sufficiency levels that may exceed DLS. Due to its (lowest) resource demand, the scenario also either outperforms or equals alternative more supply-side oriented scenarios on environmental and global commons related SDGs (SDG13, SDG14, and SDG15). As such, a high level of ambition and fulfillment of SDG12 as in LED can generate significant SDG co-benefits that are not apparent from alternative strategies with no demand-side and service delivery focus.

Figure 28 complements Figure 27 with a qualitative scenario comparison in terms of their (potential) SDG synergies and trade-offs based on the IPCC *Special Report on Global Warming of 1.5°C*. The qualitative assessment covers all 17 SDGs, where applicable, and tries to synthesize the available (albeit at times extremely limited) literature largely drawing on the IPCC *Fifth Assessment Report* (IPCC 2014).

Pathways limiting global warming to 1.5°C with no or limited warming overshoot require not only supply-side measures but also demand-side ones such as lowering energy demand, land-intensity, and GHG-intensity of food consumption. Such measures can positively impact the achievement of other societal goals such as poverty alleviation, improved energy security, as well as health benefits. Equally, measures can lead to trade-offs with SDGs if not appropriately managed.

One example of measures for lowering energy demand is introducing policies that increase energy efficiency or limit energy demand at a higher rate than historically observed. Such policies lower the mitigation cost for energy systems (Luderer et al. 2013, Rogelj et al. 2013, Rogelj et al. 2015, Grubler et al. 2018) Furthermore, in many sectors such as transport, industry, and residential sectors, strong demand-side policies that accompany supply-side mitigation policies are essential to meet a 1.5°C mitigation target while reducing the reliance on Carbon Dioxide Removal (CDR) technologies and carbon capture and storage (Grubler et al. 2018, Wachsmuth and Duscha 2019). In its 2018 *Special Report on Global Warming of 1.5°C*, the IPCC shows emission reduction pathways that assume low energy demand (as a result of demand-side measures) yield the lowest carbon prices (Rogelj et al. 2018). Furthermore, investment required for supply-side measures could be lowered if strong policies to limit energy demand growth are implemented (Grubler et al. 2018, McCollum et al. 2018).

Figure 28 illustrates such SDG interactions, between demand- and supply-side mitigation measures on

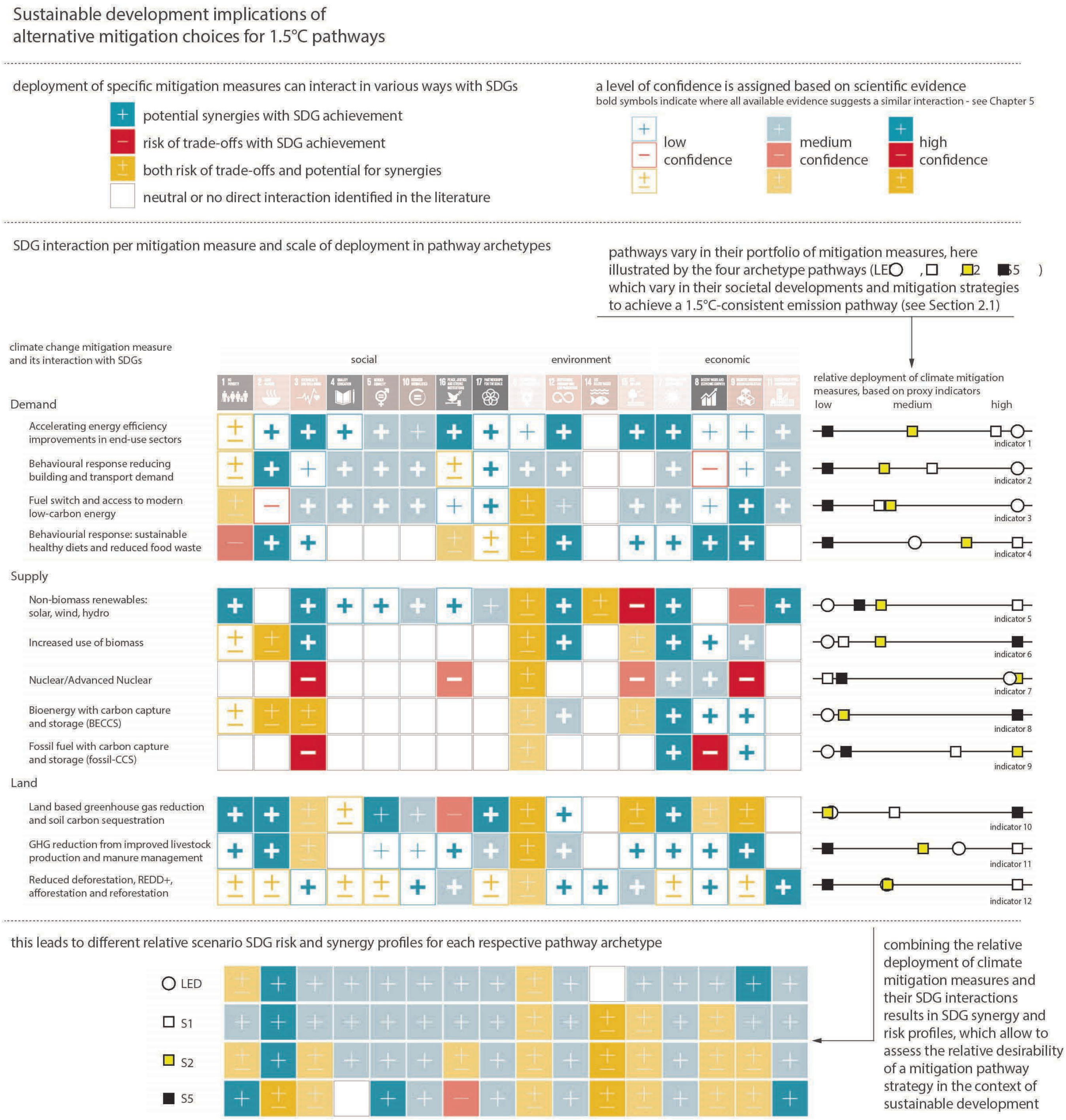

Figure 28. SDG implications of alternative strategies of limited global warming to below 1.5°C. Source: IPCC Special Report on 1.5°C, Rogelj et al. (2018), Figure 2.28.

the one hand and SDGs on the other, using the four illustrative pathways highlighted in the IPCC Special Report. The figure shows how different mitigation measures under all pathways can generation synergies and/or trade-offs with various SDGs. Such interactions vary for the same mitigation measure depending on the pathway.

For example, looking at the supply-side measure of increased use of biomass (on the left-hand side of the figure), illustrates the potential to increase pressure on land and water resources, food production, and biodiversity and to reduce air quality when combusted inefficiently.

Meanwhile, mitigation actions in energy demand sectors and behavioral response options with appropriate management of rebound effects can advance multiple SDGs simultaneously, more so than energy supply-side mitigation actions.

Looking at supply-side land-use measures such as reducing deforestation, REDD+, afforestation, and reforestation, these have the potential to reduce access to affordable and clean energy as well as clean water and sanitation, in addition to increasing poverty and hunger.

Comparing two pathways (via the right hand and the lower panels of Figure 28), one that assumes low energy demand (LED pathway) with another supply-side measures dominated pathway, S5, shows that the LED pathway displays the largest number of synergies and least[6] number of potential trade-offs. Meanwhile for the S5 pathway significantly more potential SDG trade-offs are identified. Generally, the higher the emphasis on demand reductions and policies that incentivize behavioral change, sustainable consumption patterns, healthy diets, and relatively low use of CDR the more synergies with individual SDGs can be achieved. In other words, the choice of the mitigation measures portfolio can have positive (when demand-side based), or indeed negative (e.g., when CDR based), spillovers to other societal goals. It is important to note that uncertainties regarding the extent of such SDG interactions remain substantial. Various studies suggest that carefully coordinated policies and implementation strategies are required in order for positive SDG spillovers to be realized and negative ones to be avoided (Shukla and Chaturvedi 2012, Clarke et al. 2014, McCollum et al. 2018).

3.4.4. Impacts of demand-side transformation on upstream and supply-side systems

Because of fundamental interdependencies and linkages between demand and supply, the services-oriented demand-side transformation as illustrated above in the Low Demand Scenario also provide a number of tangible benefits on the supply-side of resource processing systems as well. These include:

- Over-proportional leverage effect of demand-side resource conservation on supply-side resource use
- Enabling and accelerating structural change in supply-side systems toward decarbonization
- Increasing flexibility and resilience in upstream supply-side technologies
- Accelerating the SDG transformation processes throughout the entire system through higher use of granular options that turn over much faster than lumpy supply-side technologies.

We discuss each of these systems benefits below.

Leverage effect of demand-side resource conservation on supply-side resource use

Because of inherent conversion losses along the entire service-provisioning system, improvements in service delivery at the end of the supply chain, that is, at the service demand level, have over-proportional impacts on the supply-side inputs. These impacts, or leverage effects, are a function of the compounded conversion losses over the entire resource provisioning system that are substantial (see Section 3.4.1 above), yielding an upstream leverage effect up to typically a factor 6–7. Thus, saving one unit of output (resource use at the level of service provision) can conserve up to 6–7 units of inputs (resource extraction as input to the supply side of service-provisioning systems) and associated adverse environmental impacts (GHG emissions and air pollution, water and land-use, etc.).

Enabling and accelerating structural change in supply-side systems

Under continued demand growth, even record levels of investments into post-fossil alternatives have to date been unable to yield structural change in energy supply systems, as capacity and output growth of post-fossil alternatives have continuously fallen short of demand growth. Figure 29 illustrates this for renewable electricity generation into which the lion's share of public policy support and induced investments have been flowing over the last two decades. With the exception of the year 2009, where as a result of the demand contraction following the 2008 financial crises, growth in renewable electricity output (for 'new' renewables including wind, solar, and geothermal, as well as for all renewables together, also including conventional hydropower) actually substituted fossil fuel electricity generation, and ever larger record numbers of renewable electricity generation have been outpaced by demand growth. Noticeable and accelerated structural change in supply systems (e.g., as evidenced by declining emissions and other adverse impacts) is therefore enabled by a service-oriented efficiency strategy that lowers resource demands in absolute terms. In contracting markets, investments into sustainable alternatives can lead to rapid structural change. Changes in dietary preferences and food demand (e.g., lowering red meat consumption) will likewise underpin successful resource conservation efforts and a reversal in land-use changes and agricultural water use and losses (see Box 12).

6 The trade-off shown for the demand-side measure "Behavioral response: sustainable healthy diets and reduced food waste" on SDG1 (no poverty) is based on a single reference from IPCC (2014) arguing that healthier diets and reductions in food waste could jeopardize traditional animal husbandry in parts of sub-Saharan Africa. The argument on this potential trade-off is unsupported by other literature and also counterfactual. Dietary changes and reductions in food waste are prime concerns for affluent societies of the Global North. Traditional animal husbandry is not integrated into international food trade and hence remains unaffected by dietary regime changes outside sub-Saharan Africa.

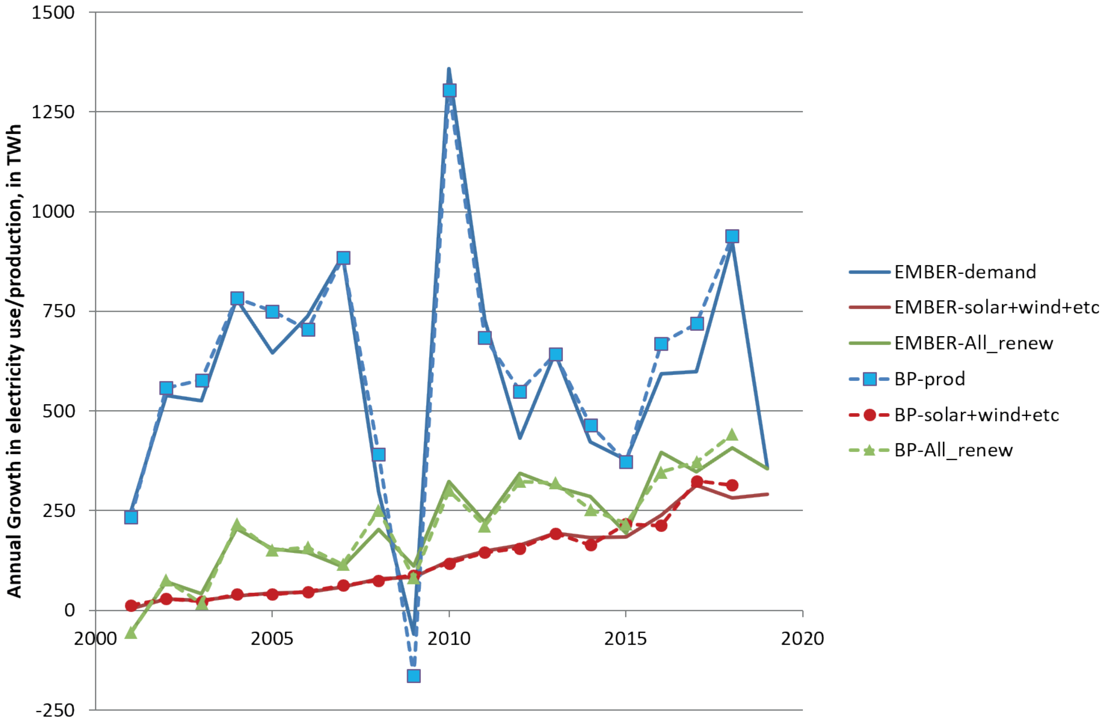

Figure 29. Interannual change in global electricity demand (blue), 'modern' renewables (wind, solar, geothermal, red) and total renewable electricity production (including hydropower, green), in TWh. Changing quantities are reported by the following year, i.e. changes between the year 2000 and 2001 are reported for the year 2001. The graphic compares two data sources, one from an environmental post-fossil NGO (EMBER) and a predominantly fossil fuel company (BP). Both data sources agree that with the exception of 2008–2009 where electricity demand was reduced as a result of the 2008 financial crisis, demand growth has persistently outstripped even record numbers of expansion of renewable electricity generation over the last 20 years. As a result, no impactful structural change in electricity supply was possible and emissions continued to grow. Source: data from EMBER (https://ember-climate.org/reports/) and BP (2019). Graphic courtesy Arnulf Grubler.

Increasing flexibility and resilience in upstream supply-side technologies

Lowered demand also significantly increases flexibility and resilience of supply-side systems, particularly in cases of innovation failures, such as, anticipated technological options do either not materialize, remain uneconomic, or are unacceptable on social or environmental grounds. This has been demonstrated in the scenario studies performed under the auspices of the Global Energy Assessment (GEA 2012, Riahi et al. 2012). Figure 30 contrasts the (high demand) GEA Supply Scenario with the (low demand) GEA Efficiency Scenario to 2050. Next to differences in demand, both scenarios are also characterized by two alternative perspectives on the evolution of transportation technologies: conventional and advanced (e.g., electrification) transport systems. For each of these two scenario variants alternative so-called 'technology knock-off' scenarios were developed in which a range of 10 alternative supply-side options were assumed not to be available for future energy supply. Examples of options 'knocked off' the supply portfolio included nuclear, BECCs, unlimited biofuels (and hence land-use conflicts), among others. The significant finding was that only under the low demand GEA Efficiency scenario, future energy supply remains robust across all 20 'knock-off' scenario variants, that is, supply remains feasible even under a (significantly) restricted supply-side technology portfolio. Conversely, in the high demand GEA Supply Scenario, especially under conventional transport technologies, the unavailability of a range of supply-side technologies ('knock-offs') resulted in infeasibilities, that is, the high level of energy demand could no longer be met with a restricted supply-side portfolio in 8 out of 10 cases, with only 2 scenario subvariants remaining feasible. With lower demand therefore supply-side systems become more flexible and tolerant to the exclusion of supply-side options thus increasing their resilience.

Harness the benefits of granular (small unit-scale) options

Demand-side transformations also enable harnessing particularly the benefits of granularity. The concept of 'granularity' (akin 'small is beautiful') has recently been demonstrated to be of particular relevance in accelerating low-carbon transformations (Wilson et al. 2020a). Granular, that is, small unit-scale technologies

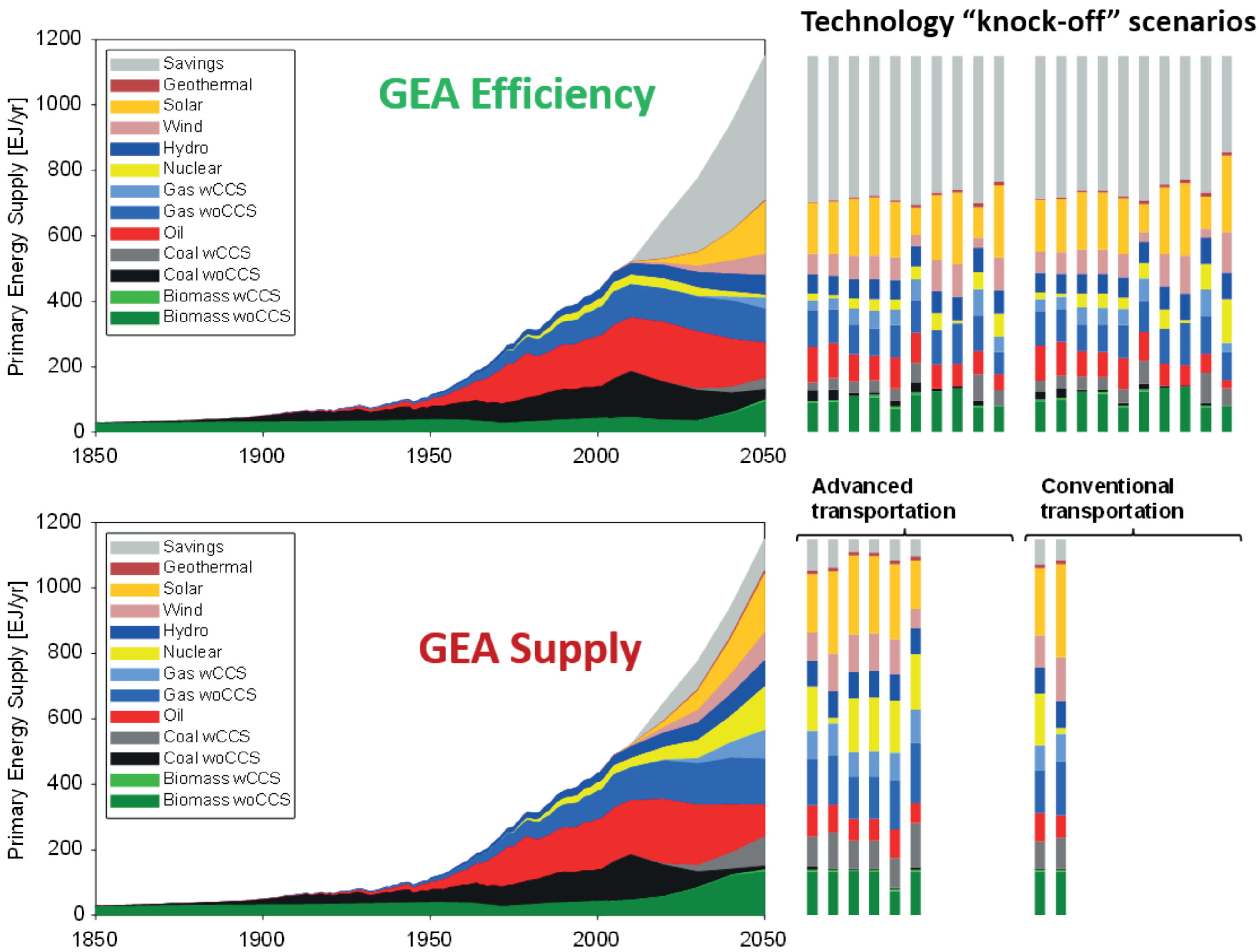

Figure 30. Contrasting the low demand GEA Efficiency Scenario with the high demand GEA Supply Scenario. Evolution of primary energy use 1850 to 2010 and in the two scenarios to 2050 (in EJ). Stacked bars show the corresponding energy supply by 2050 in a range of scenario sensitivities in which alternatively various supply-side options are assumed not to be available (are 'knocked off' the available technology portfolio). Altogether 20 scenario subvariants were calculated differentiated for conventional and advanced (e.g. electrification) transport systems. In the low demand GEA Efficiency Scenario all 'knock-off' variants remain feasible, whereas in the high demand GEA Supply Scenario only a limited set of scenario variants remained feasible, especially in the conventional transport scenario setup. Source: Riahi et al. (2012).

support accelerated systems transformations through three main mechanisms: they enable exit from lock-in into existing systems (technologies and practices), they allow for rapid deployment and diffusion, as well as enjoying greater social legitimacy due to their associated employment and beneficial economic spillover effects. Wilson et al. (2020a) examine 10 indicators in these three dimensions of granularity benefits and demonstrate empirically how smaller-scale technologies could accelerate systems transformations.

Figure 31 illustrates three examples of their granularity indicators associated with accelerated systems transformations: shorter technical lifetimes leading to faster technology turnover; higher learning rates (cost reductions with accumulated deployment); as well as greater equality in availability and access (increasing social legitimacy). All three factors: faster capital turnover, faster improvements, and higher social acceptance of granular options enable a significant acceleration of systems transformations. While the benefits of granularity accrue to all options, irrespective if these are supply-side or demand-side ones, demand-related technologies are generally much smaller in scale and thus much more granular than supply-side technology options.[7] Hence demand-side approaches to sustainability transitions enjoy the advantage of better being able to harness the benefits of granularity.

7 Counterexamples of 'lumpy' (large unit-scale) demand-side technologies include wide-body aircraft or skyscrapers, or, conversely, solar PV, as 'granular' technology on the energy supply side.

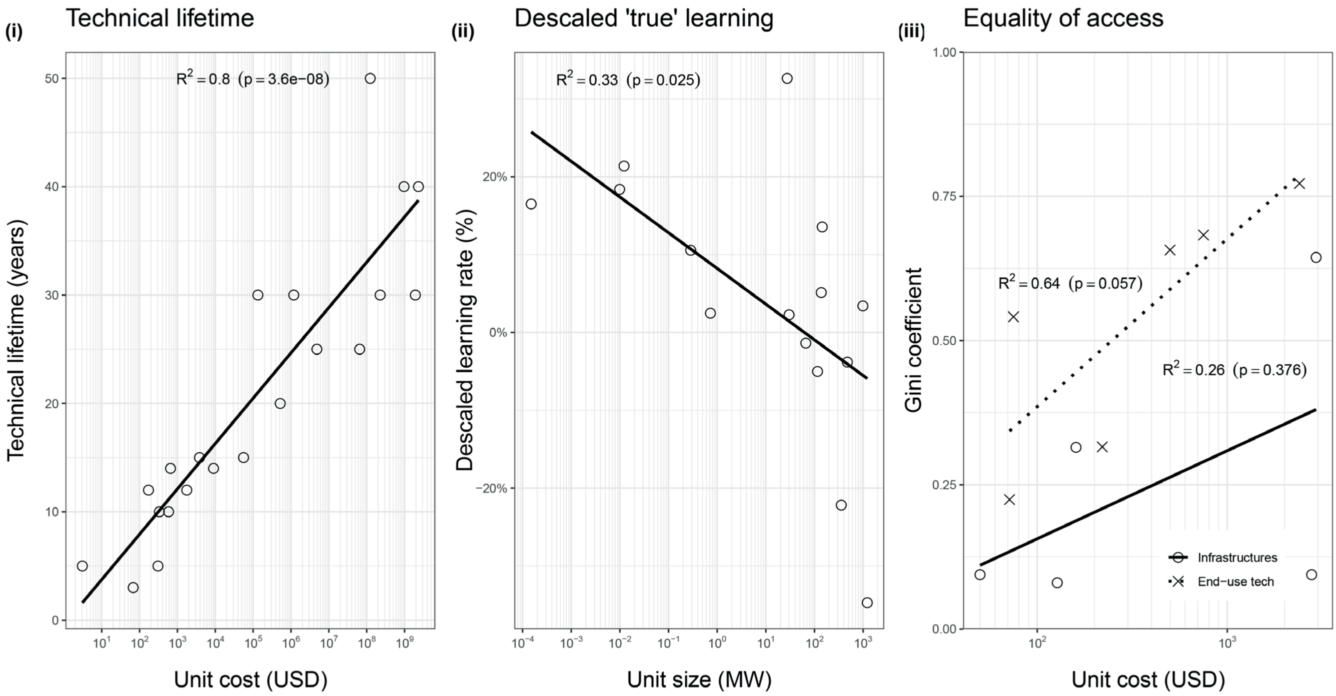

Figure 31. Three example indicators of granularity benefits (out of 10 examined in Wilson et al, 2020a). Smaller-scale, 'granular' technologies tend to have shorter lifetimes (Panel (i), implying faster turnover of capital stock), have higher learning rates (cost reductions per doubling of cumulative output, the cost reductions shown in panel (ii) correct for economies of scale effects and therefore represent 'true' learning rates), and enable higher equality of access (Panel (iii), low unit scale times low unit costs imply low cost barriers and hence higher affordability of access for the poor and thus more equitable access). Source: Adapted from Wilson et al. (2020a).

3.5. Summary

This chapter has elucidated the types of innovation required across the Six Transformations to ensure a sustainable, equitable, and resilient future with an emphasis on efficiency, sufficiency, and demand reduction. By taking a demand-based services approach, rather than a supply-based product approach, the chapter shows that providing DLS for all can be achieved sustainably at significantly lower cost and fewer environmental impacts than current business-as-usual scenarios. However, given the current development trajectory and vested interests, the necessary innovations highlighted in this chapter will not eventuate without direct intervention—that is, they need to be managed and socially steered in the right direction. This is the topic of the next chapter, which outlines the requisite changes and innovations in governance and institutions required across all sectors and at all levels, from local to global, to enable the transformation to a sustainable future.

For years, normality has been stretched nearly to its breaking point, a rope pulled tighter and tighter, waiting for a nip of the black swan's beak to snap it in two. Now that the rope has snapped, do we tie its ends back together, or shall we undo its dangling braids still further, to see what we might weave from them?

Charles Eisenstein, March 20, 2020

4 Innovation in political systems, governance, and society[1]

Global crises such as the COVID-19 pandemic are gamechangers. They hold opportunities and risks for inventions and innovation for the transformation to sustainability. Similarly, the pandemic's political implications are also likely to be a turning point for the Six TWI2050 Transformations. Many political systems around the world are at a critical crossroads that will lead to either more inclusive or exclusive societies and to substantially more or less effective governance of sustainability. At the same time, geostrategic shifts in global politics reinforce trends in countries and challenge the much needed inter- and transnational cooperation in the time of crisis (Bremmer 2020).

Political strengths and opportunities, on the one hand, have become obvious during the COVID-19 pandemic. Firstly, the pandemic is a swan song on *laissez-faire* free market capitalism with deregulation (Cherkaoui 2020). It is now the hour of effective political institutions and leaders from local to global levels that care about public and individual health. In addition, balancing public and individual interests when dealing with the pandemic requires trustworthy state institutions and credible political leaders on all levels. This works in many countries and regions; take, for example, the effective work of the regional African Disease Center. Some of the most successful measures to contain the COVID-19 pandemic were orchestrated at the community level through honest reporting, cooperation, and information sharing, for example, in South Korea, Taiwan, Province of China,[2] and Singapore (WHO 2020a). Secondly, resilient and cohesive societies where individuals share inclusive identities, trust each other, and cooperate for the common good have been crucial in collectively enduring and overcoming stressful lockdowns (Bargain and Aminjonov 2020). In some societies trust has been increasing as a consequence of the COVID-19 pandemic because people unite and experience effective action of the state (Esaiasson et al. 2020, Khemani 2020). However, states and societies alone will not tackle crises like the COVID-19 pandemic. A strong and competitive private sector and economy helps to manage crises. For instance, debates on green recovery after COVID is much more advanced in dynamic European economies than in weaker ones with less competitive private sectors. Thirdly, the COVID-19 pandemic has made it increasingly clear that stronger science-society-policy interfaces and the exchange between different epistemic communities[3] are integral to advancing and spreading evidence-based solutions (Haas 1992, Kohler et al. 2012).

Political risks associated with the crisis, on the other hand, have increased dramatically around the world. Firstly, the pandemic has accelerated the autocratization that was ongoing before the outbreak of COVID-19, while the role of elected leaders in some democracies has been strengthened (e.g., New Zealand, South Africa). A high number of autocratic states and political leaders used emergency rulings and lockdowns to expand their political power (Brown et al. 2020, Leininger 2020). If leaders do not loosen restrictions of political and civic rights, we might soon face a world where the kind of governance we need for the long-term transformation to sustainability will be much harder to achieve, if at all. Secondly, societies are increasingly under stress, with increases in domestic and political violence. Societal resilience and cohesion will suffer further and make societies more vulnerable if negative economic, social, and ecological effects of the pandemic are not mitigated (Humphreys et al. 2020, Ide 2020). Where states and the economy are fragile, there are few chances to tackle the impacts of the COVID-19 pandemic and social inequalities—in and between nations—are likely to further increase. Thirdly, populist and nationalist leaders question empirical evidence and have been reluctant to take advice from the scientific community. They spread misinformation and foster conspiracy theories, which creates mistrust in society and leads to dangerous political decisions (Spadaro 2020). Although the importance of a solid science-policy-society interface is doubtless, it has become more difficult to realize.

1 We would like to thank Christopher Rohles and Stefan Wunderlich, two fantastic research assistants at the German Development Institute, for their support in the making of this chapter.

2 For readability, only 'Taiwan' will be used in the remainder of this report.

3 Epistemic communities are networks of knowledge-based experts who inform policymaking (Haas 1992). For instance, TWI2050 is such a network, which brings together different communities.

In this chapter, we *first* focus on the innovations in governing the implementation of the SDGs since the adoption of the 2030 Agenda in 2015. We start on this positive note to show that successful innovations in integrated SDG implementation were made and now need upscaling, regardless of the pandemic. Conceptually, we base these insights on TWI2050's (2018) definition of *transformative governance* needed for the sustainability transformation and on empirical analyses of the participating TWI2050 researchers. In so doing, this chapter mirrors the findings from the 2019 Global Sustainability Development Report, which emphasizes the crucial role of governance for SDG implementation (GSDR 2019). The *second* part of this chapter focuses on the innovations that are needed in governing the transformation to sustainability in the face of the COVID-19 pandemic. We focus on governance in the political, social, and business sphere. Here, we address three questions, which need further research and knowledge creation: What are fundamental political changes resulting from the COVID-19 pandemic and what are their implications for governing the sustainability transformation? What type of governance do we need to foster societal resilience? What does an effective science-policy-society interface look like in times of populism and nationalism?

4.1. Achievements: governance innovations for sustainability

In 2018, TWI2050 released a high-profile report that outlined the core governance features that countries needed to support the Six Transformations toward sustainability (see Box 14). Though the report did not specifically foresee a COVID-19 pandemic, it was accurate in the analysis of potential disruptions from continuing down unsustainable development paths. It thus emphasized the importance of peace, political stability, and inclusive governance as necessary pre-conditions to withstand such shocks.[4] The report also moved beyond these prerequisite conditions to underline the critical role of capable public institutions, engaged civil societies, and active partnerships with scientists and the private sector to develop the policies and plans needed for the Six Transformations. Finally, it emphasized that these multi-actor governance arrangements would also need to work across scales, levels, and sectors to capitalize on possible synergies and manage the trade-offs across different SDGs.

Since the release of the first TWI2050 report (TWI2050 2018), a few discouraging and encouraging developments have altered the context for implementing its recommendations. One of the more notable sets of discouraging trends involves the SDGs themselves. Current assessments suggest that at the five-year mark on SDG implementation progress is slow and uneven, with some evidence showing the world is moving in the wrong direction on some SDGs (UN 2019). There are only 10 years left to fulfill the 2030 Agenda. Yet recent assessments are not wholly discouraging. One of the more encouraging signs is that nearly 150 countries have presented their voluntary national reviews (VNRs), revealing ambitious lists of policies required to achieve the SDGs—including those on the efficiency, sufficiency, and innovation themes featured in this report (Elder and Bartalini 2019). Another indication is the growing understanding of how the core governance features highlighted in the 2018 TWI2050 report are affecting progress on the VNRs generally and integrated approaches to policy specifically. The next three subsections illustrate the relevance of governance for integrated SDG implementation on the national level, governing nature-based solutions (NBS) on city and regional level, and emerging business models. All have in common that the subnational and municipal governance levels are very relevant for effective SDG implementation.

4.1.1. Institutional frameworks for integrated SDG implementation

Transformative governance (Box 14) does not foresee a single institutional framework that is best suited for delivering the 2030 Agenda (OECD 2016). However, research on the effectiveness of sustainable development policies consistently underlines four main criteria that merit attention: (1) horizontal coordination across policy sectors (e.g., UNDP 2017); (2) vertical coordination across levels of state and government (e.g., UNDP (2017), ICSU (2017); (3) multi-stakeholder engagement (e.g., Dodds (2015), Beisheim and Simon (2016), Stafford-Smith et al. (2017)); and (4) high-level political leadership (e.g., Abbott and Bernstein (2015), UN (2018)). Cross-national comparisons reveal considerable variation regarding the degree to which SDG governance arrangements meet these criteria and the potential challenges arising in constructing institutions based on these principles when countries implement the SDGs or related processes (e.g., CEPEI (2020), CCIC (2018), OECD (2016)).

- *Horizontal coordination across policy sectors*. Research on the National Sustainable Development Strategies (NSDS) and Poverty Reduction Strategy Papers (PRSP) of the late-1990s and early-2000s suggests that balancing interdependencies between the social, economic, and environmental dimensions of sustainable development requires involvement of all relevant ministries. The NSDS, for instance, were typically implemented and monitored by

4 The crisis featured in TWI2050 (2018). Transformations to Achieve the Sustainable Development Goals. Report prepared by The World in 2050 initiative. Laxenburg, Austria, International Institute for Applied Systems Analysis (IIASA). focused chiefly on the Arab Spring movements which were partially related to environmental stresses.

Box 14. Transformative governance (TWI2050 2018).

Basic reforms of the economy and societies need to be based on transformative governance and guide economic and social policies and instruments. The TWI2050 Report 2018 names the most important entry points of governance reforms (Table 4). **Transformative governance is a network of state, nonstate and business actors, which is multiscalar, multilevel and polycentric. However, transformative governance is interdependent with political regimes, institutions, and states.** For instance, if an autocratizing regime limits the space of action for nonstate actors and business, transformative governance is hampered or, in extremer cases, simply not possible.

Table 4. Governance reforms.

Problems to solve	Reforms needed
Sustainability transformation as a civilization challenge	Four normative innovations: 1. Earth system responsibility 2. Global commons perspective - transnational fairness & justice 3. Anticipate impacts of decisions for many generations to come 4. Culture of global cooperation and norms diffusion through transnational governance
Flexible but stable institutions needed	Network governance fostering interplay between formal institutions and governance networks
Overcoming institutional, political, sectorial path dependencies	Building transformative alliances across sectors and public spheres (state, market and civil society) from local to global
Integrated policy-making across borders, sectors and SDGs	Polycentric, multi-scalar governance and integrated management
Deep transformations lack 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 (IO)	Reinforce multilateral cooperation; strengthen autonomy of IOs

However, the transformations toward sustainability require not only capable institutions, transformative governance strategies, and adequate policies on all levels, but also a clear understanding of potential pitfalls and resistance against change, driven by politics. Five dimensions are critical and remain unchanged (Table 5):

Table 5. It's politics, stupid!

Dimensions	Problem description
1. Vested interests	Owners of fossil fuels, beneficiaries of unsustainable businesses or lifestyles
2. Power of elites	Resistance to regulation, redistribution, taxation
3. Public – private relations	Capture by private interests, weak civil societies
4. Conflicts	Political blockades, eroding social contracts and cohesion
5. Disruptive dynamics	Deep change producing legitimacy challenges

Basic reforms for the economy (Table 6) and governance need to guide the deep changes needed to implement the 2030 Agenda in the post-pandemic era. They will be the basis for transformative governance and guide economic instruments and policies.

Table 6. Economic reforms.

Problems to solve	Reforms needed
Significant Public investments needed	Increasing and stabilizing domestic tax revenues
Doubling local, national, and global infrastructures by 2050	Investment-oriented policies; long-term oriented financing
Fighting poverty and inequalities	Redistributive policies; investments in human capabilities; focusing on the bottom 40% nationally and globally
Aligning markets with the 2030 Agenda	Re-embedding market dynamics
Stabilizing local and global commons	Commons-oriented investments and guardrails
Trusted globalization	Global and national governance to triggering inclusive development; transparent and accountable global economic governance

environment ministries. While these strategies were sophisticated in their understanding of environmental sustainability principles, they were usually weak in understanding the linkages of these principles with the social and economic dimensions of sustainable development (Swanson et al. 2004, Gjoksi et al. 2010). Similarly, PRSP demonstrated a deep appreciation of the links between social and economic aspects of development but generally offered little in the way of environmental aspects.

- *Vertical coordination across levels of state and government*. There is broad agreement in the international policy community that the integrated implementation of the 2030 Agenda will require policy coherence between different levels of government (OECD 2016, UNDESA 2018). Subnational and local governments play an important role in formulating, implementing, and delivering services. They are thus crucial in strengthening the ownership and legitimacy of SDG policies by linking the implementation of the Global Agenda to local community needs that are affected by, and can benefit from, these policies (UNDESA 2018). For this reason, strategic and effective national action for sustainable development needs to catalyze action at the subnational and local levels and manage interdependencies between levels (Swanson et al. 2004, Ongaro 2015). However, vertical integration may come at a cost. Decentralization of the responsibility for SDG implementation to lower levels of government may require additional structures, legislation and regulation, along with monitoring and evaluation. This is particularly challenging in developing countries where subnational institutions often lack the human and financial resources for expanding mandates.
- *Multi-stakeholder engagement*. There is general agreement that building and implementing the integrated visions and strategies that are needed to support sustainability transformations requires a broad societal consensus. Such a consensus can only be achieved through the engagement and meaningful participation of major societal groups, including businesses, trade unions, academia, and civil society organizations. At the most basic level, awareness about, and ownership of, the SDGs by the whole of society needs to increase if the 2030 Agenda is to succeed. Equally important is engaging the private sector to close what are significant investment gaps (Sachs and Schmidt-Traub 2015); engaging science for evidence-based policymaking is equally important (Colgazier 2016a; see Chapter 4.3).
- *High-level political leadership*. Research on the National Councils for Sustainable Development (NCSD), which were created in the follow-up to the Rio Earth Summit in 1992, indicates that leadership by the Center of Government (CoG) is conducive to effective policy coordination. Moreover, NCSDs with ministerial members proved more successful in securing an integrated government approach to sustainable development when given strong support by a head of state (Osborn et al. 2014). By contrast, NCSDs located within a specific ministry often lacked leadership and the political power to effectively coordinate sustainable development matters (UNDP 2017). However, the top-down approach of relying exclusively on the CoG for the coordination of sustainable development policies may produce adverse, centralizing effects, as local governments or sectoral agencies are often best placed to identify and reconcile conflicts over issues and policies where they possess intimate knowledge (Peters 2015).

As noted previously, one of the encouraging developments is that it is possible to see whether and to what extent these criteria are reflected in the structures and processes of SDG implementation. Based on the VNRs from 2016 and 2017, Breuer et al. (2019a) answer this question by systematically mapping and comparing the national SDG coordination bodies of 62 countries. The largest group of countries opted for a rather top-down and exclusive governance model where the national SDG coordination body is located at the CoG and involves the participation of three or more ministries. However, this body rarely grants formal and permanent membership to subnational governments or nonstate stakeholders. Such an institutional design provides favorable conditions for high-level political commitment and cross-sectoral coordination but may undermine social inclusiveness and policy coherence.

Another finding from the review of the VNRs is that ministries of foreign affairs and environmental protection are more frequently represented in national SDG coordination bodies than other line ministries. The assignment of responsibility to ministries of foreign affairs is reasonable because the SDGs are an international and development policy agenda that requires considerable coordination among implementing states. However, this raises the question of whether national SDG implementation bodies are more interested in showcasing SDG-related activities internationally than in achieving multisector and multilevel coordination domestically. A related finding is the prominent role of environment ministries suggesting that the SDGs are often still perceived as an environmental agenda despite clearly broader aspirations and scope. This review suggests both that it is more challenging to meet the four main criteria in practice and emphasizes the pitfalls from trying to do so. It also may shed light on why there has been limited progress on the SDGs and on implementing innovations despite significant efforts to advance policies and strategies reported in the inherently cross-sectoral VNRs.

4.1.2. Governance innovations of nature-based solutions

A related set of queries following on from the previous subsection is whether the same set of four criteria are needed for a narrower set of integrated solutions to a range of societal and environmental challenges, including protection against losses from climate-related and geophysical hazards. Nature-based solutions fit this characterization well. They capitalize on nature to complement or substitute for traditional 'hard' or 'gray' infrastructure responses to hazards and disasters. Much like the strategies in the VNRs, their implementation arguably requires working across sectors, scales, levels, as well as leadership to arrive at a transformative solution to a pressing—albeit narrower—set of challenges.

Three case studies of large-scale NBS implementation (Martin et al. 2019) illustrate which of the previously mentioned dimensions of governance played a role in the successful implementation of NBS:

- Mitigating flood risk through the restoration of the Isar River in Munich, Germany
- Reducing landslide risk with natural measures in Nocera Inferiore, Italy
- Halting deforestation and encouraging afforestation as measures to reduce flood/landslide risk in the Wolong Nature Reserve in China.

While the substance and context of the cases differ, several of the key governance features played a role in all three of these success cases. These factors are described below.

Firstly, there was coordination and cooperation across space and agency remits to deliver financial and other forms of support needed to bring solutions to scale (Corfee-Morlot et al. 2009). In each case, novel approaches to public administration were adopted that involved working across multiple scales and/or sectors to include flood and landslide protection as well as nature conservation, urban planning, water quality, waste management, tourism, recreation, and more administrative responsibilities. In the Isar case specifically, the regional and municipal water authorities collaborated on a far broader vision for the Isar river than their customary gray infrastructure solutions for flood protection. This collaboration was initiated by ecologically committed staff members who formed a multiscale and cross-sectoral working group that broke down the silos of water and urban planning. Bridging these remits was impressive by itself but even more so given the project's magnitude.

Secondly, there was meaningful participation of all persons and institutions with a stake in the outcome: multi-stakeholder engagement (Reed 2008). Stakeholder participation can range from providing a two-way dialogue to codesigning strategies and projects. In Germany, Italy, and China, innovative stakeholder participatory processes emerged that co-determined the design of NBS. In Italy, the process coupled stakeholders and experts in an unprecedented codesign of the eventual NBS over an intensive three-year process (Linnerooth-Bayer et al. 2016, Scolobig et al. 2016). In China, local authorities designed and implemented incentives for households in consultation with villagers for community-based monitoring of illegal logging in a nature reserve. The unique system complemented the traditional 'sticks' approach for sanctioning illegal logging with 'carrots' in the form of payments to household groups who then had clear incentives to prevent logging in their assigned forest areas.

Though the cases underline many of the same features as the VNRs, they—and the broader research on NBS—point to additional sets of factors that may prove influential in creating opportunities for NBS but also other attempts to advance transformative solutions to sustainability challenges in the COVID-19 era. First, major external jolts are a *window of opportunity for nonstate actors and a moment to demonstrate political will effectively.* Already active environmental groups or sympathetic state authorities can take the opportunity and advocate for a nature-based or hybrid green-blue-gray solution. Political will (though to different degrees) was reinforced by individuals that championed innovative nature-based policy options. Both a shock to existing governance arrangements and a greater role for politics could help break 'gray lock-in' (Martin et al. 2019). Second, *sufficiency is important to protect resilience of natural systems*. There is an analogy with COVID-19. When the pandemic struck, many countries and institutions found that they did not have sufficient stores of protective wear and other critical material. Likewise, for environmental crises, we need abundant 'stores' in terms of ecosystems, such as wetlands, species diversity, etc. There is need of transformative governance to protect the resilience of natural systems. In particular, there is a need to manage the conflict between resilience and 'cost-effective solutions.' It has been a focus on cost-effectiveness, which removed stores of medical equipment before the outbreak of COVID19, and replaced ecosystems with monocultures.

4.1.3. Emerging business models for solving societal problems

There are new business actors aiming to solve societal problems. They are key actors of transformative governance. For example, social entrepreneurs,

Box 15. Excursion: TWI2050 – integrating governance and political conflict in future scenarios.

Modeling alternative future development scenarios on the basis of integrated assessment models (IAMs) is highly relevant to inform necessary policy processes for the implementation of the 2030 Agenda. The interdisciplinary developed Shared Socioeconomic Pathways (SSPs) play a key role in this context as they provide a set of five different scenarios that outline alternative socioeconomic development narratives as well as quantitative pathways of GDP, and demographic and educational developments. Along with the SSPs possible future pathways—especially with regard to climate change and global emissions—are examined by various research communities (for a recent visualization see https://www.climatescenarios.org/). Some elements of delayed policy implementation and degree of international cooperation are also part of the model-based SSP quantifications in the literature.

Despite the broad social science evidence that political factors such as political institutions and armed conflict are closely linked to economic development (see Acemoglu and Robinson (2012) and Collier and Hoeffler (2004)), current development projections do not sufficiently account for these factors as quantified drivers (Beck and Mahony 2017). This is not least due to the fact that projecting and modeling future developments do not have a strong tradition in social sciences given the difficult and complex unfolding of this type of change. Quite recent approaches to estimate regime transitions (V-Forecast: Predicting Adverse Regime Transitions, PART) or violent conflict (Violence Early-Warning System, ViEWS, of the Department of Peace and Conflict Research, Uppsala University) are taking up this issue.

However, not considering the effects of armed conflict and governance on economic development can strongly influence the results of current pathways along the SSPs and weaken their value for informing necessary policy processes to achieve the transformation to sustainability. Researchers from the modeling community are already aware of this gap (Dellink et al. 2017) and first attempts to take 'good governance' or 'civil conflict' into account are notable (Andrijevic et al. 2019, Hegre et al. 2016). Still, future research should concentrate on the deepened integration of political drivers and—building on the results—the development of new (sub-)narratives for more realistic scenarios.

start-ups, and venture capital firms that employ emerging technologies and new business models to seek social returns in addition to economic ones. Financial resources have emerged, focused on returns beyond pecuniary value, such as social investors, environmental social governance funds, social impact funds, and crowdfunding, to name a few. There are knowledge appropriation tools that allow more open access to innovation for further use or sharing for public purposes (e.g., creative commons licenses, open and free source movement). Rules and regulations have emerged to focus on societal impacts of innovation or economic activities that reach beyond country and disciplinary boundaries, such as international standards addressing environmental, social, and ethical issues, including environmental certification and social labeling, sustainable and ethical business codes of conduct, such as fair trade. Advances in digitalization may also help to establish new certification schemes, including monitoring and verification, along complex value chains.

New governance mechanisms allow experimentation of new innovative solutions to diminish the time lag of users to benefits from the products and services, such as regulatory sandbox and regulatory pacing (Marchant et al. 2011), agile governance[5], application of virtual reality simulations for policy, and participatory/open governance (e.g., Port Alegre, Brazil and Quebec, Canada). New business models have been created by the digital economy and the sharing economy, such as peer-to-peer reciprocal services, customized and decentralized small lot production that can respond to unmet needs quickly, such as makerspaces (see example of 3D visor printing in Chapter 1), decentralized power generation, and various forms of financial inclusion using mobile phones (e.g., M-Pesa and Go-pay) with accompanying e-commerce services, to name a few. Indeed, these developments have been made possible by emerging technologies that are said to have the potential to transform society, such as ICT, 3D printers, and AI (see also the above section on digitalization, Chapter 3 on new business models and TWI2050 (2019)). Currently, the 'signal' is still a relatively isolated force but in a short space of time, these dots are being connected to manifest transformation from the bottom up in a variety of combinations. This is expected to occur more rapidly in the Global South than the Global North owing to the sheer necessity of overwriting the inhibiting factors, namely, institutional inertia, vested interests, and habits.

The question then becomes how such combinations are achieved so that they can gradually transform systems to generate broader impacts. The key is to design and configure different combinations of modules that not only generate new knowledge, but also generate positive externalities and network effects, work with external actors (Prahalad and Mashelkar 2010), and capture benefits (Teece 2018). Here, innovation ecosystems and types of complementary assets play an instrumental role (Teece 2018). Clear economic incentives through transparent and credible policy instruments, like pollution taxes, would certainly

5 Global Future Council on Agile Governance: https://www.weforum.org/communities/global-future-council-on-agile-governance.

help to accelerate the widespread implementation of these new opportunities.

Samurai Incubate Africa is one example of a number of emerging business models that generate their own ecosystems to solve societal problems. Samurai Incubate is one of Japan's pioneers in bringing new business models and start-up expertise to emerging economies. It was established in 2008 as an incubation program but soon created its own venture capital fund. It was a successful frontrunner in incubating venture capital in Japan, investing in ICT related early stage start-ups when this area of work was not well established. It expanded its activities to Israel in 2014 and subsequently into Africa in 2018. Samurai Incubate Africa started in 2018 and is now about to enter the second round of funding in 2020.[6] Samurai Incubate Africa invested in MPost, a start-up that creates virtual addresses with mobile phone numbers to deliver a postal service in Kenya where the majority of people do not have physical addresses. To complement this strategy, Samurai Incubate Africa's invests in start-ups in digital payment, mobile delivery services, and e-commerce, because these are essential stepping stones for creating the value chains of e-commerce. In other words, the company tries to create markets while filling in missing services to make its prior investment sustainable (see Chapter 2).

4.2. Innovations of governance post-COVID-19

The recommended features of governance have not changed significantly since the publication of the first TWI2050 report (2018, TWI2050 2019). In fact, the current sociopolitical climate arguably has made deepening and broadening those recommendations more vital. A stable, peaceful, and inclusive set of institutions has become essential to limit threats to public health and safety. The involvement of multiple actors working across the sectors, scales, and levels is also more critical to identify and act upon the synergies between health and other socioeconomic goals. But while staying the course on these prerequisite conditions makes sense in general, current trends require modest modifications in particular.

Those particular adjustments require taking note of some of the more discouraging trends that have surfaced since the COVID-19 outbreak. These trends include a notable rise in autocratic tendencies, the fracturing of societies, and a palpable distrust of science in some countries. If these trends continue, transformative governance as outlined above will be difficult—if not impossible—to achieve. Against this backdrop, this chapter first examines some of the political threats to transformative solutions to sustainability challenges in the wake of the COVID-19 pandemic. It then offers proposals and visions for models of transformative governance. It concludes with an outlook at the relevance and future of an effective science-policy-society interface.

4.2.1. Acceleration of political risks through reactions to the COVID-19 pandemic

The most significant set of challenges lies in a clear shift toward more autocratic political systems as a consequence of lockdowns and emergency responses in several countries (Crabtree et al. 2020). We underline these shifts because less democratic societies will make innovations that can drive sustainability transformations more difficult. These risks also merit attention because the centralization of political power and restrictions on civil rights can undermine the collective learning processes and networks of intellectuals and public deliberations needed for innovation and transformation (Leininger 2020). In addition, context-sensitive approaches have proven to be very effective to tackle the pandemic. In this report, we give aggregated and more general insights, which need to be adapted to individual cultural, political, and socioeconomic contexts. For instance, Box 16 provides insights into path dependencies of East Asian countries.

Recent research shows concerns about these risks are well founded. The "Pandemic Backsliding Risk Index" of the V-Dem Institute at the University Gothenburg demonstrates that autocratization and accompanying erosion of civil and political liberties as well as violations of human rights have accelerated since the pandemic (Lührmann et al. 2020b).[7] Research based on the index shows that 48 countries are at high risk and 34 at medium risk to autocratize further due to restrictive lockdown measures, while only 47 countries are at a low risk to become more autocratic (Lührmann et al. 2020a) (Figure 32). Risks of a pandemic backsliding are high if COVID-19 emergency responses are not proportionate, necessary and non-discriminatory, lack time limits, disregard checks and balances, and fail to hold governments and politicians accountable. For example, suspending the legislature indefinitely in countries such as India heightens risks of backsliding in the world's largest democracy (Lührmann et al. 2020a). The above trends are even more worrying because the index does not account for changes within closed autocracies.

6 They selected projects focused on solving societal problems with the innovative application of technology and business models. Another unique feature of their investment is investing along value chains to create complementarities within the invested start-ups.

7 This index combines data collected in the V-Dem network on different types of emergency responses of governments with previously existing V-Dem data on political regime classification and autocratization trends before the COVID-19 outbreak.

Box 16. Excursion: Political path dependencies – insightful examples from East Asia.

When identifying necessary governance reforms, we must not forget that political and social path dependencies shape states' and societies' policy priorities, political cultures, and governance mechanisms. Political reforms toward sustainability are an illustrative example for political path dependencies. Challenges for East Asian countries to transit to a green economy include legacies of the past authoritarianism in the Cold War era, the authoritarian expert politics, and the prioritization of economic interests (Feuer and Hornidge 2015).

Legacies of the past authoritarianism in the Cold War era have hindered the progress of social transition in some East Asian countries. In spite of democratization, many East Asian countries have not entirely transited from the previous high carbon regimes (Chou 2018). The authoritarian governance and regulatory culture remains the center of policies governing this area (Chou and Liou 2012). Governments in these countries inherited bureaucratic cultures from the authoritarian era. These bureaucratic structures tend to be conservative and therefore are not highly open to the reformation of governance. As a result, plans for deep transformation can hardly be carried out.

In addition, authoritarian expert politics have impacted the policymaking rationales of these countries. Authoritarian expert politics are still dominant in the East Asian countries. The policymaking rationales of these countries are still in the shade of developmental neoliberalism (Yao 2013). Experts and technocrats, along with academics and stakeholders, form interest complexes. These interest complexes are prone to consolidate pre-existing developmental structures and therefore make the sustainability transition more difficult. The cases of structural disasters (Matsumoto 2012, Matsumoto 2013) and man-made calamities (Funabashi 2012) such as the 'nuclear village' in Japan (Hasegawa 2015, Hasegawa 2018), the 'nuclear mafia' in South Korea (Ku 2018) and the 'nuclear complex' in Taiwan (Chou 2018) exemplify the impact of an expert politics structure on energy transformation.

The prioritization of economic interests of the East Asian governments also challenges the social transformation. The East Asian post-developmental states tend to adopt pathways prioritizing economic interests and overlook environmental impacts in the policymaking process (Hornidge 2011, Chou 2015). The ideology of economic development priority and the brown economy with the massive use of brown energy form locked-in regimes and make societies of these countries into 'compressed modernization' in South Korea (Chang 1999, Chang 2010) or 'delayed hidden risk societies' (Chou 2000, Chou 2002, Chou 2018). There is a need to also pay attention to the impact from the prioritization of economic growth, loose risk regulations, and nationalism, as Beck (2014) highlighted as the hidden coalition between neoliberalism and nationalism.

While East Asian's authoritarian technocratic past has resulted in a science-policy-society interface that has enabled a science-based and whole-of-government approach toward managing COVID-19, such development also required these countries to be awakened from their state of 'delayed risk.' In the case of Taiwan, top-down government coordination with businesses was key in spearheading the growth of a mask production strategy (from a daily production of 1.8 million in early-2020 to 20 million by May 2020), as well as in providing the impetus to push biotechnological companies toward higher-value device and drug production, for COVID-19 test kits and vaccines. On the other hand, because the legacy of an authoritarian past still defers governance to one that is top-down, greater space for bottom-up participation would therefore need to be developed and legislated—for instance, doctors in Taiwan had to protest for their rights to be protected when a blanket travel ban was enacted on them in response to perceived manpower shortages due to COVID-19. As such, governance innovations would be required to enable social transformation for countries on their path dependencies.

Although there is a substantial number of countries with low or no risks (in green), the picture becomes less promising when looking at the number of people affected by high and medium risks of pandemic backsliding. Figure 33 illustrates the magnitude of those risks. It shows that 38% of the world's population live under a high risk of pandemic backsliding, while 20% live under medium risk. Considering that 25% already live in closed autocracies and only 14% in low-risk countries, the prospects for political conditions fostering a transformation are definitely in question.

A closer look at individual countries also paints a troubling picture. Several of the leading global and regional powers, including eight G20 members, are in the high and medium risk groups, while two additional G20 members are closed autocracies. Table 7 further shows that countries with large populations are characterized by a strong or medium risk of pandemic backsliding. Most of these high and medium risk countries are shaping the global order and providing important global public goods—for example, Brazil and the Republic of Indonesia are home to the world's largest rain forests. As the rain forest example suggests, shifts to autocracy will not only influence progress on the SDGs and the transformation to sustainability within but also beyond their borders.

4.2.2. Governance innovations for post-COVID-19 stimulus packages and social transformation

We started this chapter with political risks and threats emerging from the COVID-19 pandemic and their implications for innovation and transformation. There have nonetheless been some positive signs emerging from the crisis. A potentially powerful driver of change is that governments have committed to approximately $7 trillion in recovery stimulus packages—a figure that is close to three times the size of the estimates of the $2.5 trillion funding gap per year for achieving the SDGs calculated prior to the pandemic (Figure 34).

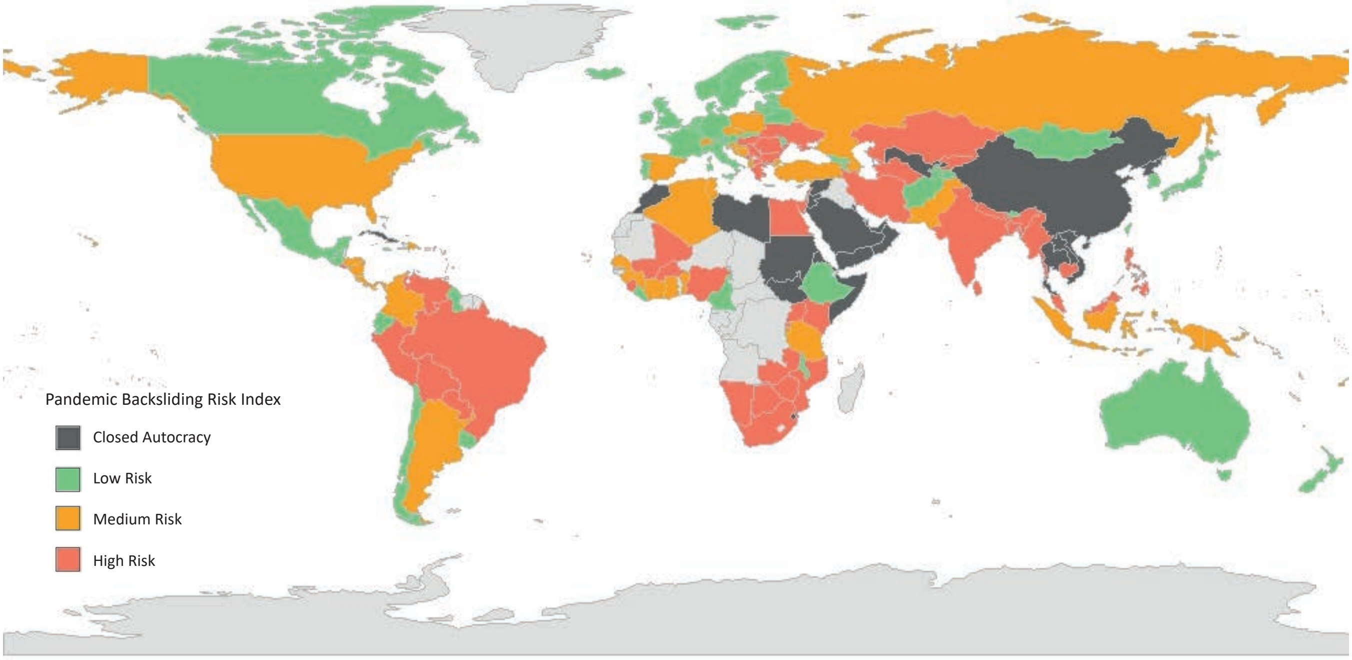

Figure 32. Risks of pandemic backsliding worldwide. Displayed are the country assignments according to the Pandemic Backsliding Risk Index by Lührmann et al. (2020b) for 154 countries into three risk categories (green, orange, red) and a fourth 'Closed Autocracy' category (black). The index describes the risk of autocratization due to restrictive lockdown measures. It combines data collected in the V-Dem network in 142 countries with the existing V-Dem 'Regimes of the World' measure (v2x_regime) and further draws upon the already existing Liberal Democracy Index (v2x_libdem) to identify prior autocratization trends. The Regimes of the World measure is used to define the 'Closed Autocracy' category (v2x_regime = 0). Source: The rworldmap-R-tool was used for the mapping of the data (South 2011). Graphic courtesy of Christopher Wingens.

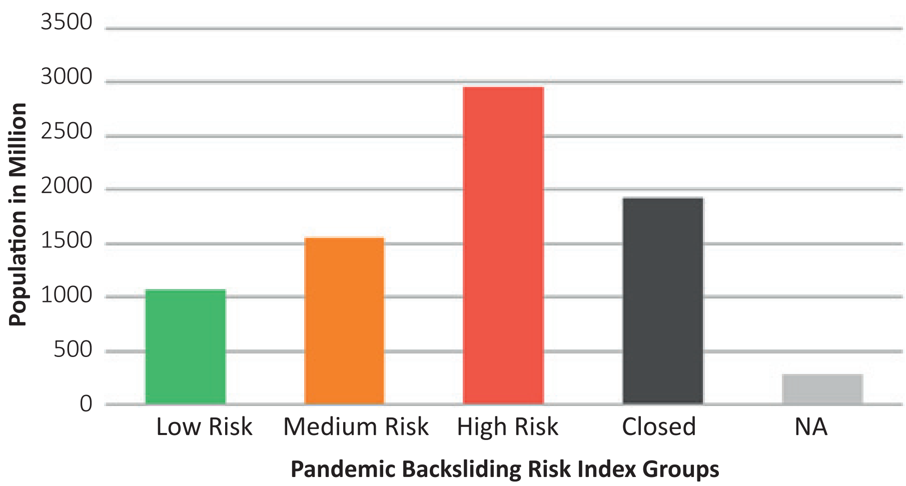

Figure 33. Population distribution in different Pandemic Backsliding Risk Index groups in million in 2020. A total of 175 countries are considered. Source: Own compilation based on Lührmann et al. (2020b) for the Pandemic Backsliding Risk Index and the UNDESA (2019) World Population Prospects 2019 Revision for the population data in 2020.

Equally important as the size of those resources, is that COVID-19 has created a window of opportunity to allocate stimulus funds to greener (new deal) programs and policies promoting efficiency, sufficiency, and innovation. Whether financial resources are distributed for more sustainable purposes is not guaranteed, however; it will depend on policy and political reforms discussed in this section.

Sufficiency policies and governance reforms

In the near term, policy changes may come before political reforms. This is chiefly because time is of the essence and policies often change faster than political institutions. Ensuring that sectoral policies are coherent with policies promoting innovation and transformation as part of the COVID-19 recovery is a useful step forward: incoherent policies can lock in

Table 7. The five most populous countries per Pandemic Backsliding Risk Index group. Source: Own compilation based on Lührmann et al. (2020) for the Pandemic Backsliding Risk Index and the UNDESA (2019) World Population Prospects 2019 Revision for the population data in 2020. For readability short UN names are used.

Country	Pandemic Backsliding Risk Index Group	Population
India	High Risk	1,380,004,352
Brazil	High Risk	212,559,424
Nigeria	High Risk	206,139,584
Bangladesh	High Risk	164,689,376
Philippines	High Risk	109,581,080
USA	Medium Risk	331,002,656
Indonesia	Medium Risk	273,523,616
Pakistan	Medium Risk	220,892,336
Russian Federation	Medium Risk	145,934,464
Turkey	Medium Risk	84,339,064
Mexico	Low Risk	128,932,752
Japan	Low Risk	126,476,464
Ethiopia	Low Risk	114,963,584
Germany	Low Risk	83,783,944
United Kingdom	Low Risk	67,886,008
China	Closed Autocracy	1,439,323,776
Vietnam	Closed Autocracy	97,338,576
Thailand	Closed Autocracy	69,799,976
Sudan	Closed Autocracy	43,849,260
Morocco	Closed Autocracy	36,910,560

vested interests and divert stimulus recovery packages to business-as-usual development (OECD 2018). A related need is to consider a mix of market-based, command and control, and informational instruments. Such mixes can work on multiple drivers and appeal to multiple stakeholders, bringing about wide-ranging changes to public health and related policies (Rogge and Johnstone 2017, Edmondson et al. 2019).

An important area for COVID-19 recovery where these more general policy design principles on coherence and instrument mixes can be applied is what are called '*sufficiency policies.*' This refers to policies and measures that promote ecologically sustainable consumption patterns and bring benefits to a substantial share of the population by altering unsustainable habits. Another characteristic of these policies is that they not only seek to influence consumers but also companies and third parties. Sweeping changes are needed because behavior depends both on personal factors like ingrained values, attitudes, and routines as well as social norms, the organization of work, and a host of technical, economic, infrastructural, and political conditions. Ideally, sufficiency policies would contribute to, and be influenced by, the shift to more innovative systems that themselves allow multiple elements and stakeholders to interact. To illustrate, the recent shift from business-related travel to online video that has followed COVID-19 restrictions is an example of sufficiency-related behavioral change that could bring about longer-lasting changes in mobility habits together with other policies that encourage flexibility in work-related travel.

As the above business travel example implies, some of the desired changes depend on unpredictable factors. Yet, as that example underlines, policymakers also need to take advantage of opportunities with deliberate policy changes. Paralleling the previous discussion, some of these changes would aim to make existing policies more coherent with the goal of sufficiency—for instance, curbing incentives for unsustainable travel in energy, labor, and social policies. At the same time, policymakers will also need to introduce incentives and regulations to bring about a shift to more innovative systems. Also echoing the previous discussion, a mix of instruments ranging from *information-based instruments* (advertising, campaigns and websites and product labeling) to *economic instruments (*excise taxes and charges; schemes with tradable allowances; subsidies) to *regulatory instruments* (*de facto* bans on conventional light bulbs; setting of limits (on living space, energy saving); product standards) would help advance sufficiency.

In the area of sufficiency policy specifically, an additional set of instruments is also needed. Those instruments should target planning and infrastructure provision as both areas can lock in unsustainable behaviors and planning. One potential approach would

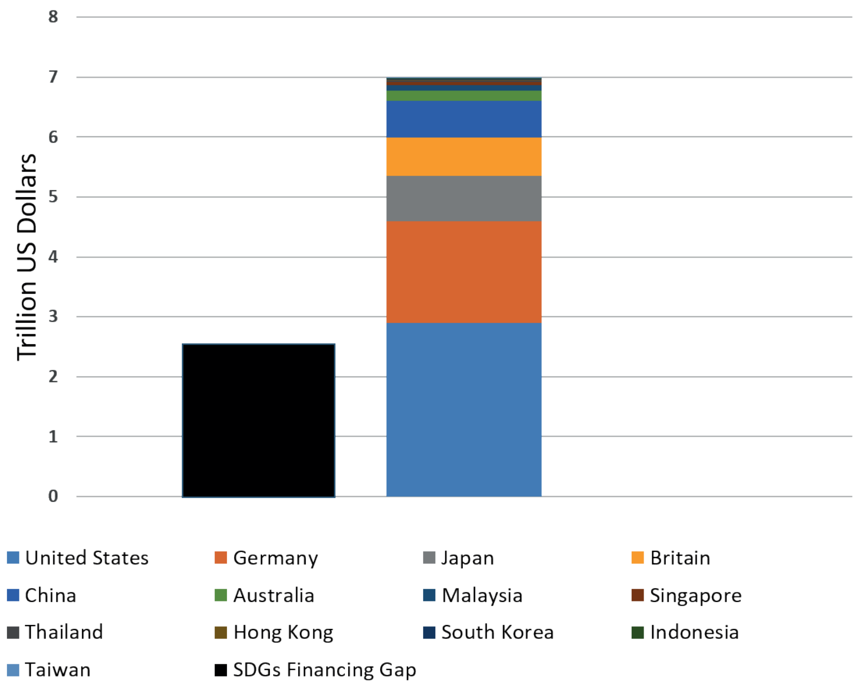

Figure 34. Investments in recovery stimulus packages and SDG funding gap. Source: based on data from Subhani (2020) and Wilson (2016).

follow work on nudging and involve policymakers making sufficiency the default option in consumer decisions when they are the service provider (e.g., urban planning can encourage behavior switching to pedestrian and bike-friendly measures). Another alternative is that municipalities may want to actively promote services for collaborative consumption (e.g., in the food sector) that favor sufficiency. In both of these cases, carefully crafted governmental interventions can induce participation and lend direction to search processes for solutions to challenges to sufficiency.

While the above suggestions should facilitate the adoption of sufficiency policies, there are barriers to their uptake. One such obstacle is that a key benefit of sufficiency and efficiency—environmental protection—is chiefly long term and socially distributed, whereas many of the costs are near term and concentrated. There are hence likely to be strong and powerful interests opposing sufficiency-related reforms, especially in resource-intensive sectors—though the COVD-19 crisis and the allocation of stimulus funds could weaken their influence. An additional challenge is that poor or disadvantaged groups may be hurt when sufficiency policy leads to an increase in the prices of essential goods and services (i.e., energy, food, or travel costs). Limiting these undesirable social impacts should be considered in the effort to make policies coherent (for a broader perspective see Box 17). Another possible stumbling block is that changes in consumption patterns and innovations supporting sufficiency could also be argued as infringing on individual liberties and run into constitutional and legal challenges. These are just one of the ways in which policies interact with the larger political system and speak to the need for coherence not only among policies but also between policies and institutions.

Entry points for sustainability breakthroughs in the face of the COVID-19 pandemic

Sufficiency policies may take time to be effective because they require fundamental individual and societal transformations of behaviors, attitudes, and values. A rapid and abrupt transformation of societies and governance is imperative to achieving the SDGs. Researchers (Otto et al. 2020)}have developed social tipping points, which are instrumental for the successful achievement of the SDGs (Figure 35). They define social tipping points as spreading processes in complex social networks of behaviors, opinions, knowledge, technologies, and social norms, including spreading processes of structural change and reorganization (Otto et al. 2020). These spreading processes resemble contagious dynamics observed for COVID-19, and once triggered, such processes can be irreversible and difficult to stop. They argue that the COVID-19 pandemic provides an opportunity for strengthening social tipping points, which can enforce the transformation to sustainability. While the study on social tipping points first focus on policy enforcement and the relevance of social movements for change in several domains, a later study proposes a polycentric model of governance for achieving social transformation to sustainability (Bhowmik et al. 2020) (see next section).

Box 17. Entry points for the Six TWI2050 Transformations: sparing, sharing, and caring.

Governing the transformation to sustainability is highly complex. The nonlinear character of society and governance as well as the diverging entry points of a country's transformation to sustainability demands that the historical context in understanding transformation be emphasized. Applying the conservation tools introduced by (Green et al. 2005) three governance typologies can be considered according to their entry points to transformation to sustainability: Sparing, Sharing, Caring. Each of these three reflect different arrays of governance structures, institutions, and even cultures. They represent 'world regions' defined by the distinct set of regimes and other governance structures that emerged through historical experiences following multiple transitions. Although the 'efficient world region' (sparing) prioritizes economic transformation, the 'strong world region' (sharing) prioritizes its political transformation, and the 'cohesive world region' (caring) prioritizes its social transformation, these world regions are equally viable pathways to sustainability.

This means that sustainability is attainable for all countries regardless of their position in a world region (Hernandez 2020). There are different sets of policy instruments available for these countries due to path-dependent governance structures. In addition, it is possible for countries to shift membership to a world region depending on long-term policy shifts. In general, these narratives confirm the existence of multiple sustainable futures, each of which adequately reflects different levels, degrees, and paces of political, social, and economic transformation.

Sparing refers to a cluster of countries where policies are oriented toward improving efficiency and maximizing value added. This cluster is driven by the main logic that networks (and not primarily the state) can best provide solutions. The state cannot be a rule enforcer and a player at the same time. Countries belonging to this cluster tend to institute economic transformation to consolidate distinct market dynamics to achieve an 'efficient economy.' *Sharing* pertains to a cluster of countries where a 'strong' central authority drives the transformation to sustainability. Strengthening state capabilities is the main goal of political transformation so that the state is empowered to 'share' not only the benefits but also the costs/risks of sustainable development. *Caring* is, in theory, positioned between sparing and sharing, but it is driven by an 'enlightened self-interest' rather than pure altruism. In this world region, countries prioritize social transformation to fulfill specific policy priorities such as social equity.

Twelve interconnected socioeconomic subsystem domains were formed, which can be further grouped into four social transformation system domains by Otto (Otto et al. 2020), and an empirical analysis of SDGs 7 (energy), 13 (climate), and connected SDGs conducted. This approach on social tipping points indicates how the existing recovery and prevention programs enacted during the COVID-19 crisis can foster rapid sustainability transformation as well as suggestions for additional 'sustainability breakthroughs' through interventions and measures that can remove backlashes for both COVID-19 mitigation, and climate and sustainability action (Figure 36). Six core social tipping interventions for which researchers found empirical evidence were consolidated, which can help in developing refined rapid socioeconomic transformation pathways and narratives customized at appropriate scales.

Political domain: Strong climate policy enforcement is the cornerstone of rapid decarbonization through eliminating the use of fossil energy from most sectors and spheres of human life. These policies can foster producer responsibility and a circular economy but can also intervene where necessary, for example by banning advertisement of fossil fuel products and abolishing the trade in fossil energy. A complete removal of subsidies for fossil fuel industries is of high urgency and these subsidies should be redirected to renewable energy generation. The COVID-19 crisis is an opportunity for enacting these policies through political enforcement. For example, while oil companies are facing a substantial loss given the reduction in mobility, governments could force them to align their business model with a 1.5°C world, and thus, remove the subsidies for fossil fuel production and mobilize them into wind and solar energy production. The same applies for the aircraft industry or car and truck manufacturers (see also Chapter 3). In addition, 'carbon bubble,' a view which holds that there exists many times more fossil fuel reserves than can be used if we are to meet international climate targets, and that as such the fossil energy industry may be significantly overvalued, is currently evidenced by the COVID-19 crisis and ongoing citizen movements. A divestment movement is already underway and several economic measures that can potentially scale up this movement can benefit both COVID-19 and climate mitigation.[8] Another example on the importance of nonstate actors is the protest of doctors in Taiwan for better provision of medical assets during the COVID-19 pandemic (see Box 16).

Information domain: Information and knowledge systems are the key for rapid sustainability transformation. Not only are science-policy-society interfaces important but also society as a whole (see Section 4.3). For example, the Fridays4Future movement led by an informed high school student Greta Thunberg

8 For example, many companies will benefit from a cut in business taxes during the COVID-19 pandemic, when a global tax on companies to help support the infrastructure needed to deal with global crises like pandemics, sea-level rise, and extreme weather events should be negotiated. This cannot only drive the divestment from fossil energy but also solve the unfairness and tax inequity. On the other hand, for companies receiving bailouts, governments should insist that once the companies are back on their feet, they invest in transitioning to a circular business model and renewables.

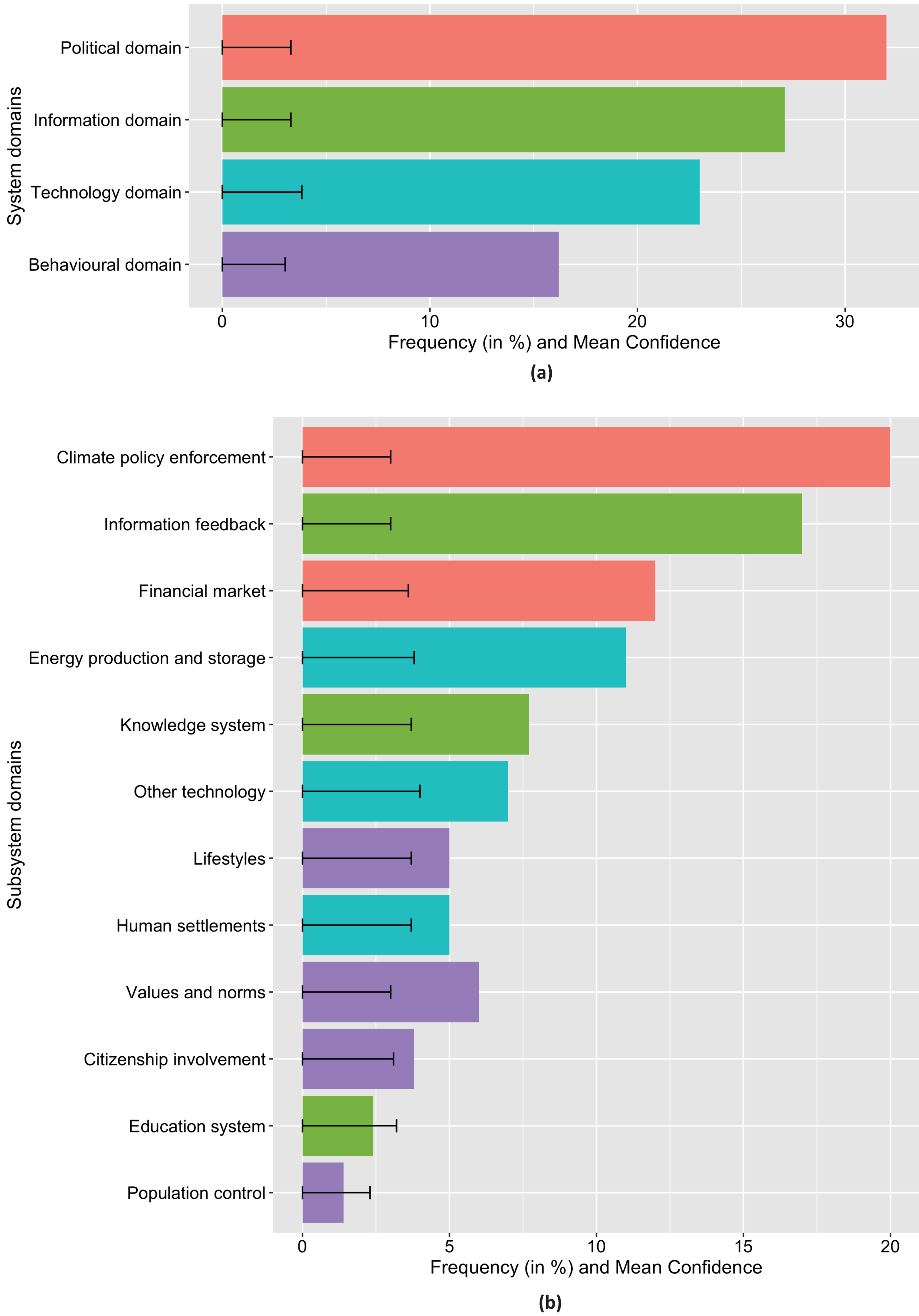

Figure 35. Social tipping points in 12 interconnected socioeconomic subsystem domains. Note: Socioeconomic transformation system (panel a) and subsystem domains (panel b) instrumental for rapid and complete decarbonization of the global energy system by 2050, are identified through responses from 212 international experts in the field, an expert workshop, and literature review (see Otto et al. (2020) for details). The frequency (colored bars) and mean confidence (black lines) in a transformation system and subsystem domain, represent the percentage of experts who indicated that system and subsystem domain, and the average value of expert assigned confidence that transformation in that domain and subdomain will take place (on a scale from 1–5, where 1 is the lowest and 5 is the highest), respectively. Source: based on Otto et al. (2020).

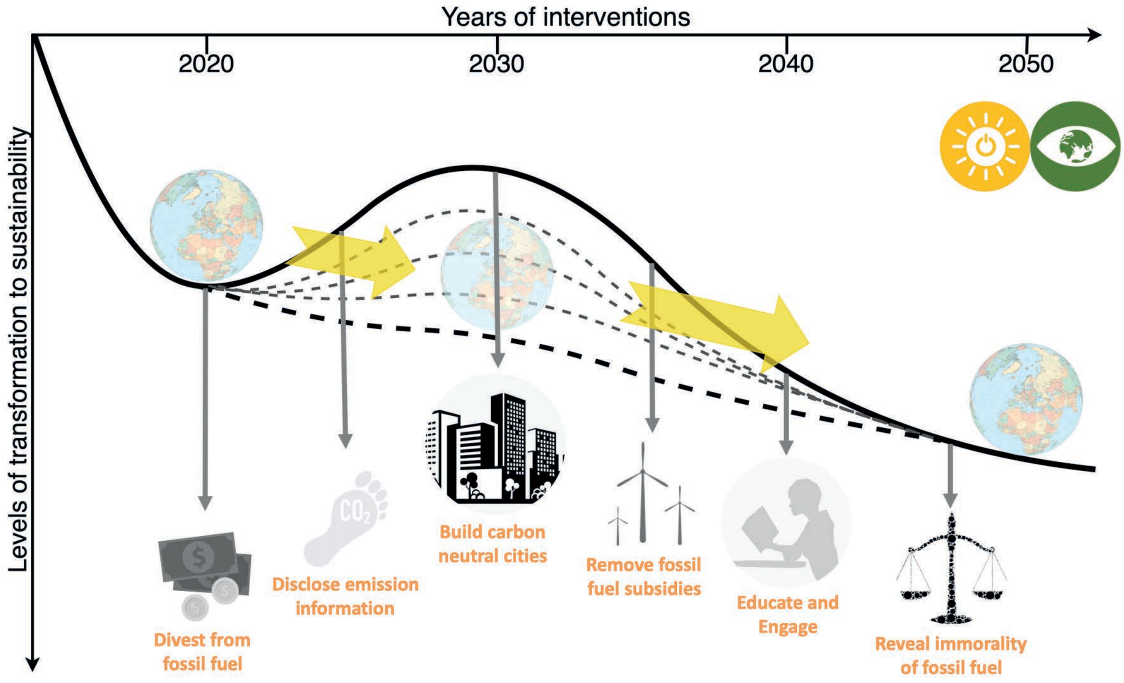

Figure 36. Six tipping interventions for sustainability breakthroughs that can potentially rapidly transform the world's socioeconomic system to achieve SDG 7, 13, and connected SDGs. The world's socioeconomic system today is trapped in a valley where it still depends heavily on burning fossil fuels, leading to high rates of GHG emissions. The interventions have the potential to erode the barrier through triggering social tipping dynamics in different sectors and thus paving the way for rapid transformative change. Source: adapted from Otto et al. (2020), graphic courtesy of Avit K. Bhowmik.

achieved global impact. Information feedbacks are critical, such as labels related to 'Earth Facts' and disclosure of information regarding individual carbon footprints and emissions on the products we consume like those used for nutritional facts. For example, regulation of advertising could include as mandatory indicators of sustainability of products and services in the way energy labeling and efficiency indicators are required in the EU. In addition, our knowledge system should include and enrich new world views such as reconnecting to the biosphere, modern shamanisms, and indigenous approaches to nature. This should go hand in hand in transforming our education system by integrating climate change into the broader processes of history, politics, and economics. To fight the COVID-19 crisis, some countries are now willing to share information openly, and public awareness of that shared data is crucial to fight pandemics and increases pressure on governments around the world. This potential in information sharing could be expanded for fossil energy production, usage and emission information, as well as for sharing good examples of sustainability transformation and solutions. Like the current global effort to produce and distribute medical equipment, sustainability solutions and strategies can be globally produced and shared.

Technology domain: Our energy production and storage systems are currently being transformed through the exponential diffusion of renewable energy, distributed generation and efficient systems, local energy cooperatives, and community driven solar and wind projects, and especially in the end-use demand and provision of energy services (see Chapter 3). Local entrepreneurs and public-private partnerships should engage with these efforts to make the energy transition faster and swifter. Digitalization of the economy through technologies like tele-working, e-mobility, artificial meat, multipurpose farm-ponds etc., which can be sustainably produced, can drive a rapid reduction in energy demand (see Chapters 2 and 3). Human settlements and cities are the hub of energy demand reduction (see Chapter 3). One of the biggest positives of the current crisis is the dramatic reduction of air pollution in cities. Government efforts should secure this trend, and instead of reducing congestion charges to encourage traffic back, should raise congestion charges, subsidize public transport, and incentivize people to cycle or walk in cities.

Behavioral domain: A major shift in lifestyles and the dominant paradigms that influence what is desired and valued by individuals, and how the choices and decisions taken by individuals are rewarded by the society, is crucial for rapid sustainability transformation. Shifts in values and norms are also critical. Raising public awareness to the disproportional impacts of GHG emissions and global environmental changes on the most vulnerable social groups such as women and children and for the wellbeing of future human generations can drive a major social shift to sustainability and clean energy. This can be fostered by informed citizenship involvement. Five percent of mindful consumers led to the achievement of European Union climate goals by 2020. In recent weeks, some of the most successful efforts to contain the COVID-19 pandemic were orchestrated by South Korea and Singapore, who relied on extensive testing, honest reporting and the willing cooperation of a well-informed public (see Chapters 1 and 2). At the same time, the COVID-19 pandemic has also shown some of the unintended, negative, psychological, and social consequences of confinement and social distancing. All of these positive and negative fundamental aspects of human behavior, wellbeing, and social response need to be taken into account. Thus, resistances and movements organised by the minority of the society may lead to a global network of social movements, for example Fridays4Future, and can transform the majority of the society to take actions to battle climate change and remove sustainability backlashes. . Governments could intervene by making it a condition that companies continue low-carbon working practices like working from home to reduce emissions from commuting and congestion.

A polycentric networked governance system for rapid and abrupt social transformation to sustainability

A collective achievement of the SDGs and the Six Transformations inherently requires cohesive societies that are able to integrate heterogeneous values and norms among societal groups, including religions, and nations. Cohesive societies tend to be more resilient, including to external shocks like the COVID-19 pandemic. Equally important, societies need to align with a new global identity based on shared responsibilities and a vision for a sustainable future. This also requires a great reduction of inequality within and between countries. With the accelerating inequalities driven by the COVID-19 crisis, function-based polycentric networked governance systems should complement rule-based policymaking. This approach is deemed to foster rapid and abrupt, as well as longer-term, social transformation to sustainability. It may furthermore enhance social cohesion and catalyze the transformations essential in socioeconomic domains to achieve the SDGs.

A polycentric networked governance system creates agencies across social cohorts and has relevance for both rapid COVID-19 contagion and rapid social response to the COVID-19 and sustainability crises. Recent research models a polycentric networked governance, here utilizing the ‘Powers of 10’ framework proposed by (Bhowmik et al. 2020) (Figure 37). This model meets the criteria for transformative governance as outlined in Box 14.

A polycentric networked governance system moves away from the current focus on nation states, and rather focuses on every level of society—individual to global levels. We are aware that political affairs tend to refocus on nation states nowadays (see above). Nevertheless, it is important to constantly develop visions and models for transformative governance that do justice to developments that go beyond the nation state. In particular, the focus of this multilevel approach lies in networked cities, as intermediate governance entities between nation states and local communities. There are four drivers why they are well placed to address the civilizational challenge of the transformation to sustainability: (1) the population sizes of 193 UN signatories vary by four orders of magnitude and hence, indicate different degrees of capabilities, resources, and contributions; (2) several local and community level sustainability initiatives demonstrated more success and impact than global and national level initiatives, which does not only become evident in the fight against the COVID19 pandemic but also the successful NBS cases outlined above (see Section 4.1.2); (3) governance on city level has a high capability to interconnect different policy realms such as sustainable livelihoods and job creation, environmental sustainability, sustainable energy, and sustainable consumption; and (4) implementation of sustainability action strategies demand active formation of human agencies to govern transformation, which relies on the actual size of the population in different societal levels rather than imprecise national or global measures (Bhowmik et al. 2020). Distributed global responsibilities from individual to global levels through agencies that can be formed using a Powers of 10 framework will thus enable transformation in every social sphere and implementation of SDGs across every level of society (see Bhowmik et al. (2020) for details). Note that seamless relationships with private business (10^1) and markets (10^5) are fundamental for transforming the social sphere and creating innovations.

4.3. A strong science-policy-society interface

Basic science as well as interdisciplinary research is key to identify sound and timely sustainability policies. The COVID-19 pandemic has made this more obvious than before. Scientists have become public figures and indispensable advisers to some governments and international organizations (Roehrl et al. 2020). Where investments in research and development are high, states have performed better in fighting the pandemic so far. Even though most would agree that evidence-based policy advice is crucial to overcome crises like the COVID-19 pandemic, it is not yet clear to what extent and through which institutional mechanisms political decision making and policies are shaped by

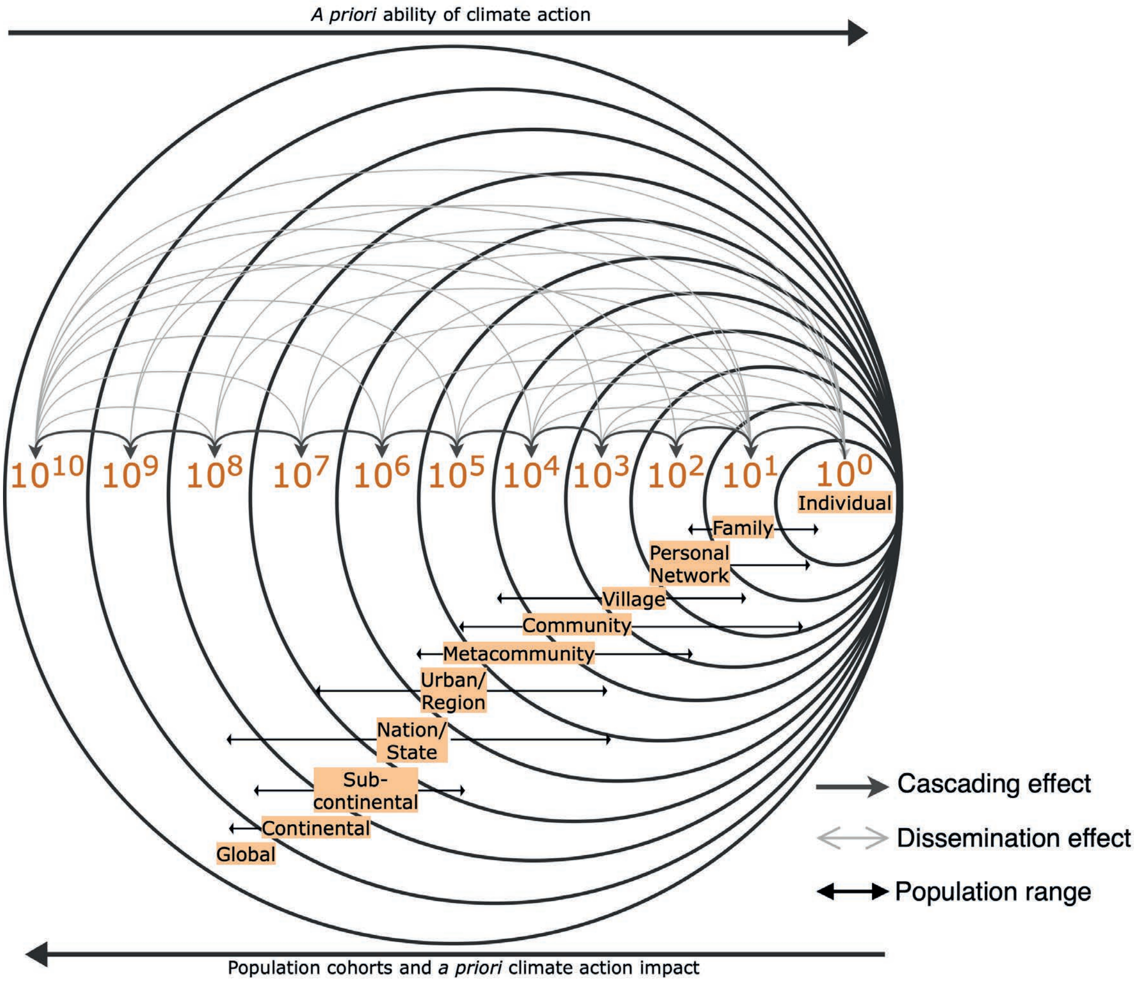

Figure 37. A networked governance approach for societal transformation Note: A 'Powers of 10' approach to form agencies and polycentric networked governance between every individual and estimated 10 billion people by 2050. The community to urban level or a community of 10,000–1,000,000 people may provide a sweet spot for maximizing the sustainability action impact through polycentric networked governance. Source: Bhowmik et al. (2020).

scientific evidence. Where the science-policy-society interface failed in response to COVID-19, we saw disastrous outcomes for public health, the economy, and international collaboration. It was astounding that so many advanced countries with highly capable science advisory ecosystems, including and especially the USA, had serious failures in responding to this quickly emerging, unexpected threat. Governments in many countries were unable to act wisely and early. Political conflicts over medical supplies and assignment of blame stymied a globally coordinated response.

In the light of global crises, two urgent questions emerge. How can we shape an enabling political environment open to critical science? What are institutional and societal mechanisms of an effective science-policy-society interface?

Credible and trustworthy science requires open exchange between individuals, data sharing without interference of vested interests from states or business, as well as constructive criticism. Also, as outlined in the previous chapters, innovations more and more depend on a network of individuals who share ideas and cocreate inventions (see Chapter 2). This suggests that academic freedom is an indispensable precondition for an effective policy-science-society interface. Academic freedom was in decline before the outbreak of COVID-19. As Figure 39 depicts, the current state of academic freedom worldwide, according to the V-Dem Academic Freedom Index, is mixed and shows strong overlaps with the distribution of democratic regimes in the world.

Where states tend to limit and restrict academic freedom substantially, the pandemic backsliding risk is also remarkably high (see Section 4.2.1). As Figure 40 depicts, most low pandemic backsliding risk countries have the highest degree of academic freedom. Low academic freedom groups mainly include medium or high pandemic backsliding risk countries or autocratically ruled ones. This might indicate that a well-established science-policy-society interface is key for states to cope with the long-term political consequences of the pandemic and actually functions

Box 18. Science-policy-society interfaces in national frameworks for SDG implementation.

Institutional frameworks for national SDG implementation should foresee an established and frequent exchange with actors who provide empirical evidence for good sustainability policies. However, an analysis of the VNRs submitted between 2016 and 2018 shows that science actors are represented in only 20% of the national SDG implementation bodies (see Section 4.1.1, Figure 38). Even in technical working groups and committees, science is only present in 15% of cases. In other words, in 64% of the countries that had submitted a VNR, science actors were not involved in official SDG implementation bodies.

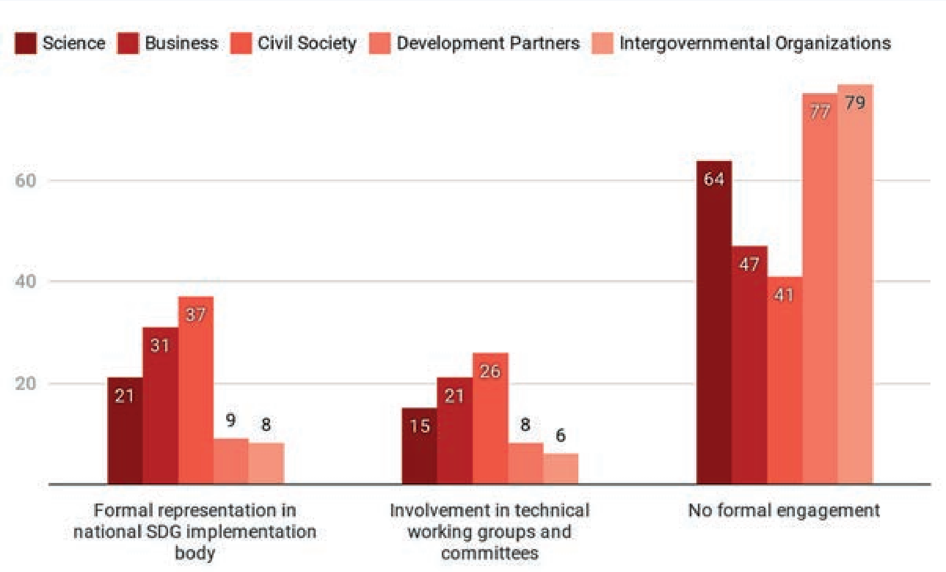

Figure 38. Engagement of nonstate stakeholders in SDG implementation. Source: based on Breuer A. et al. (2019b), graphic courtesy of Anita Breuer.

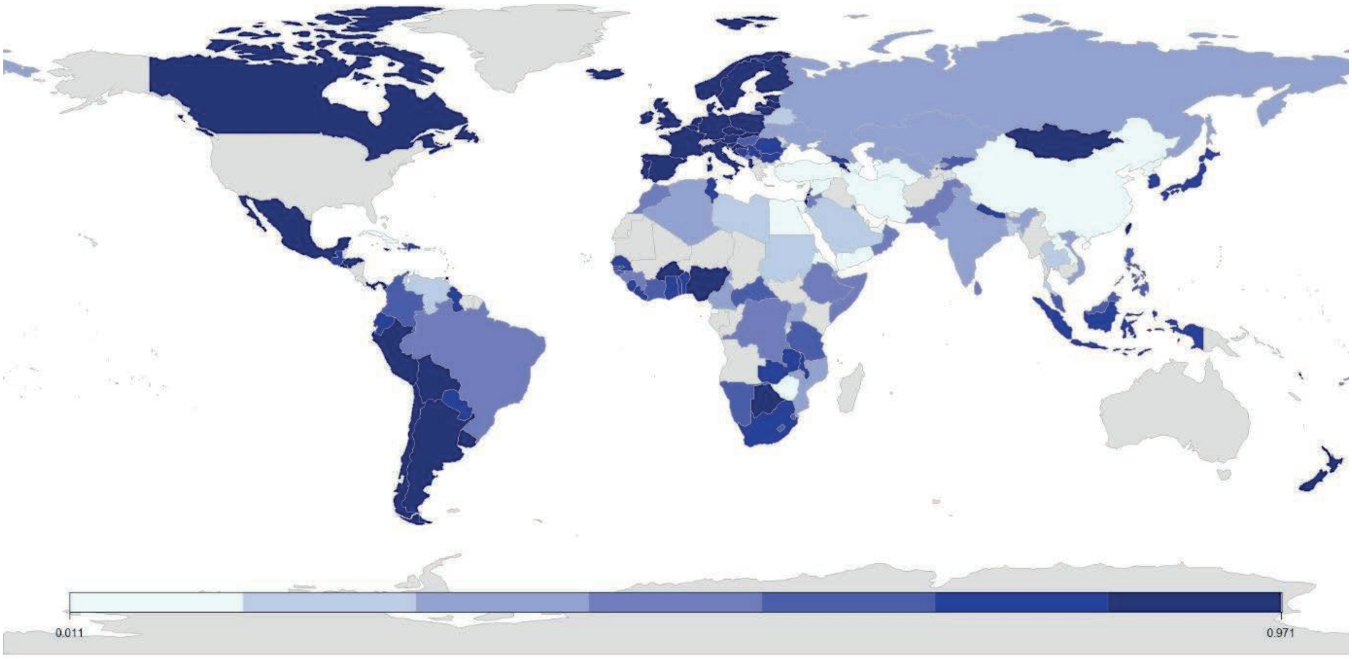

Figure 39. State of academic freedoms worldwide (2019). Displayed are the country assignments according to the V-Dem Academic Freedom Index that is included in the V-Dem Dataset v10 (Coppedge et al. 2020, Pemstein et al. 2020). The index is an aggregated measure to quantify the degree of the realization of academic freedom in a given country. It is coded from low (0) to high (1) – high values are therefore indicating a high degree of the realization of academic freedom. In total, 141 countries are considered. There is still a high number of missing countries (in gray) because the index is very recent. Future versions will include the missing countries. Source: The rworldmap-R-tool was used for the mapping of the data (South 2011). Graphic courtesy of Christopher Wingens.

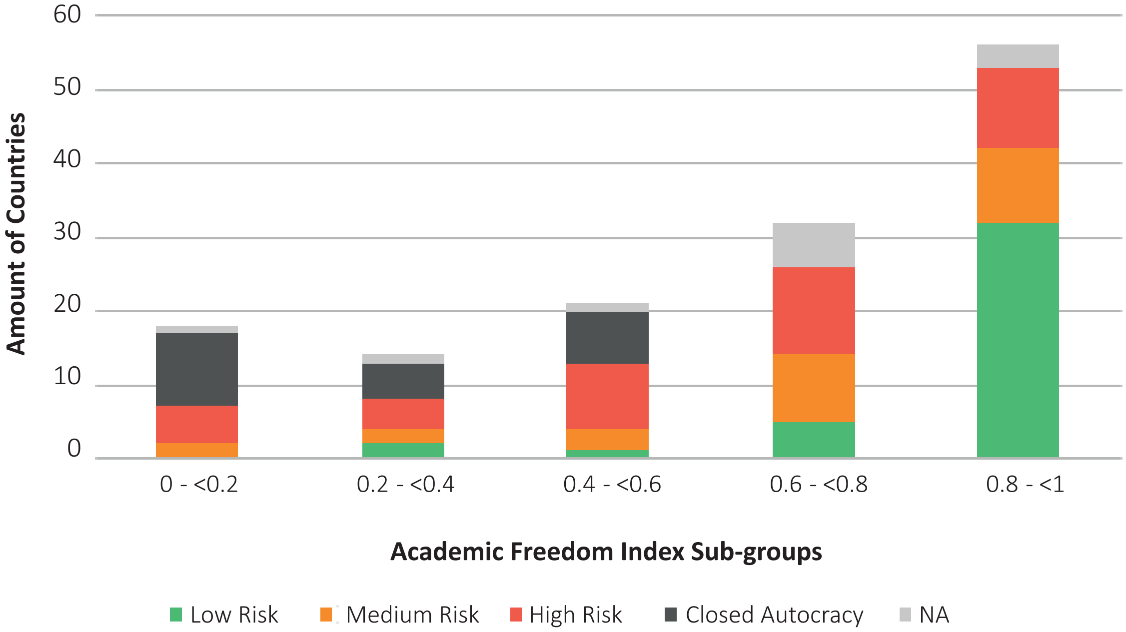

Figure 40. Number of countries in the Academic Freedom Index subgroups by Pandemic Backsliding Risk Index group (2020). Displayed are the number of countries in the Academic Freedom Index (Coppedge et al. 2020, Pemstein et al. 2020) subgroups by Pandemic Backsliding Risk Index (Lührmann et al. 2020b) assignments. Based upon the Academic Freedom Index, which is coded from low (0) to high (1), five subgroups of equal size were developed in steps of 0.2. For each subgroup the constellation of Pandemic Backsliding Risk Index assignment is defined. In total, 141 countries are considered.

as an anchor of stability. Populist and nationalist governments and heads of state who distrust and discredit empirical evidence and spread fake news to attract popular support make it difficult to establish science-policy-society interfaces. They foster mistrust in scientific institutions and individuals as well as neutral generation of evidence. The USA and Brazil are currently the most prominent examples with devastating consequences for individuals and social groups in their societies. Overall, the political context conditions for an open, critical and, thus, effective science-policy-society interface is in decline. Although designing institutional frameworks of a science-policy-society interface is important, it will not be enough. Any discussions about institutional frameworks needs to take into account the broader political picture.

The science-policy-society interface is a shorthand description of an idealized system with three components (Hadorn et al. 2008). The best scientific information and advice is provided by the most knowledgeable institutions and experts inside and outside government. That advice is acted upon by key decision makers in government and international organizations recognizing that politicians take factors other than science into account. The decisions of the government or international organizations are communicated to the public in a candid, trustworthy way with trade-offs and uncertainties recognized. Prior to 2020, the 10 actions viewed by many analysts as most important to strengthen the science-policy-society, mainly on the national level, were (Colglazier, 2016a):

- Appoint a highly competent chief science adviser to the head of state and create an advisory committee of nongovernmental scientists and technologists to assist the chief science adviser
- Appoint science advisers for each of the relevant government ministries and connect them in a network with the chief science adviser
- Create civil service positions for individuals with scientific and technical backgrounds for serving in government ministries
- Provide fellowships for young and mid-career scientists, engineers, and medical professionals to experience working in government
- Solicit independent scientific advice on key policy issues—both science for policy and policy for science—from the most respected nongovernmental scientific and technical institutions in the country, and have that advice made public
- Create a unit with scientific and technical professionals to serve the legislature on issues where scientific input is needed
- Encourage scientific professional societies to present awards for high-quality science journalism
- Encourage universities to create courses on science and technology policy and train students for careers that combine competence in science and technology with knowledge about policy in the public and private sectors

- Encourage the domestic scientific and technical community to engage and collaborate with the best scientific and technical communities around the world
- Utilize science and technology to help solve regional and global problems as well as to help improve relations between countries.

Then came the pandemic. The above top 10 actions might have been necessary elements, but they proved not to be sufficient to prevent the early failures in responding to COVID-19. With hindsight coming from the searing experience of 2020, it now seems clear that the list needs a preamble to emphasize prerequisites for achieving an effective global science-policy-society interface (Ullah 2017). First, the science-policy-society interface must be fit for transnational science cooperation if it shall help to address global crises and to achieve the sustainability transformation. Second, we need to move from a largely supply-driven, linear standard model (Figure 41, panel A) about the relationship between science and society to a more fluid, reflexive and pervasive engagement of stakeholders (as an active proxy for society). We need to develop demand- and problem-driven, solution-oriented science, which then is actively taken into consideration in decision making and policymaking (Figure 41, panel B). Rather than being a passive actor concerned only with scientific discovery, in this model science would play an increasingly active role. It would engage in the codesign and coproduction of knowledge to diagnose problems; to devise options for technical and policy solutions; and to help chart various possible future pathways to choose from, as well as creating trust in scientific results (Taylor et al. 2017). As outlined above, one of the main challenges will be to create continuous, long-term partnerships based on trust in order to advance science. Therefore the focus needs to shift from consultation to continuous, and potentially institutionalized, transnational and disciplinary collaboration (Scholz et al. 2020).

In the face of autocratic, populist trends, pandemic backsliding, and decreasing academic freedom, creating the 'triangle approach' is demanding. Five important prerequisites need to be considered:

- Creation of a culture of trust and shared values between scientists and the public as well as between scientists and decision makers (which may require scientists to listen more to the public and for decision makers to understand the needs, values, and multiple perspectives of citizens) (Colglazier 2020)
- Creation of an international environment that boosts global capacity for all sciences and improves cross-border collaboration for transdisciplinary and diverse research (including easing visa requirements for researchers, funding for international cross-disciplinary scientific grants, investments in exchange programs, and training for researchers on policy advice) (Scholz et al. 2020)
- Restructure and align global science organizations such as the International Science Council, the Inter Academy Partnership, and the Sustainable Development Solutions Network (SDSN) with the SDGs (Scholz et al. 2020)
- Creation of a duty for scientists to communicate clear and accurate information to the (global) public regardless of decisions and communications coming from government (Colglazier 2020)
- Creation of an incentive structure for scientists to ensure that the public and the government are promptly made aware of the opportunities, challenges, and threats that are seen from the rapidly advancing knowledge of science and technology (Colglazier 2020).

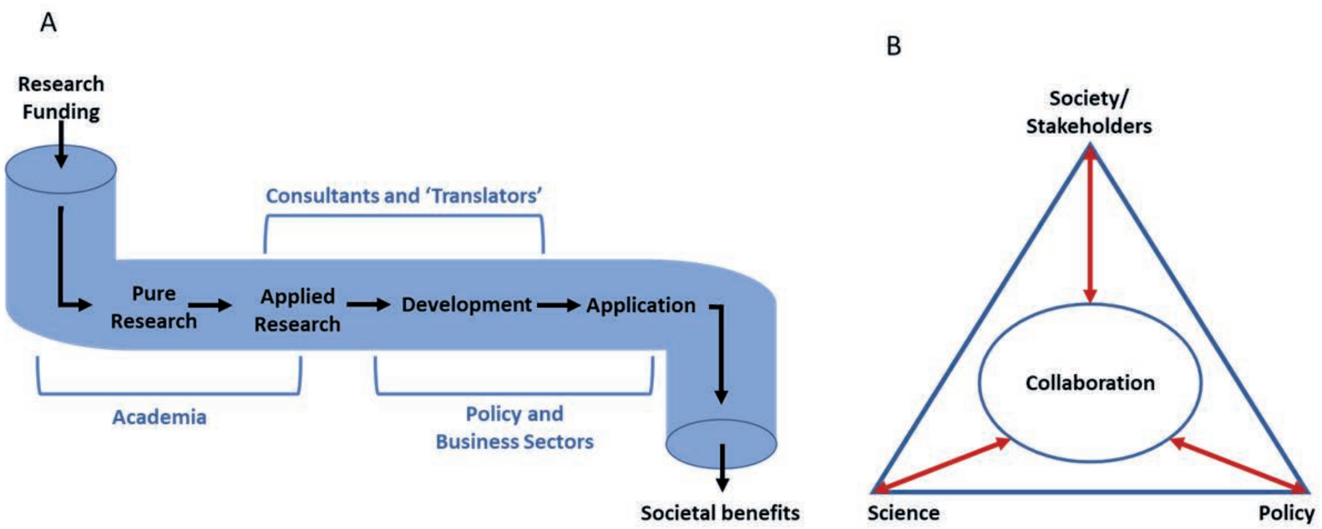

Figure 41. From a standard linear model (A) to the Science-Policy-Society Triangle (B). Source: Ullah (2017), adapted from Hessels and Van Lente (2008).

Efforts to strengthen the science-policy-society interface at the global level have emphasized most of these elements. They are needed in order to share knowledge and data, to promote collaborative research, to ensure universal access to solutions, and to act with greater urgency on global scientific assessments (Roehrl et al. 2020). Moreover, international cooperation and exchange can also help to share good and bad experiences in a joint learning process across countries of very different cultures and historically emerged governance systems. Policy advisers must not only present accurately the state of scientific knowledge with its uncertainties to decision makers and the public, but also clearly state where the advice incorporates value judgments that go beyond science (Colglazier 2016b). Credibility is the most precious asset for an individual or an institution that provides effective and trusted science advice.

4.4. Summary

This chapter has elucidated the tension between the achievements in transformative governance since the adoption of the 2030 Agenda and the current global political trends, which make it more difficult to achieve the transformation to sustainability. It shows that innovations in governing the SDG implementation have taken place. Many states have introduced institutional frameworks, which emphasize horizontal coordination across policy sectors, vertical coordination across levels of state, multi-stakeholder engagement and high-level political leadership; nature-based solutions have become more popular and new business models have emerged. Although the COVID-19 pandemic has accelerated negative political trends such as global autocratization and polarization of societies, it has also provided opportunities for effective sufficiency policies and for accelerating social tipping points for a transformation to sustainability. It underlines the need to invest more in a global science-policy-society interface, which informs evidence-based policy making through higher investments in research and development, the creation of trust in science, the restructuring of global science organizations, and a change of the incentive structures of scientists to improve the communication of research results to the public.

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1. The world is at a crossroads – achievement of the 2030 Agenda is possible but requires accelerated action and transformative pathways for sustainable development.
2. A just and resilient sustainable future for all – entails socioeconomic development for improved human wellbeing while preserving Earth-system resilience.
3. The COVID-19 pandemic is a great threat to humanity – but it provides an opportunity for change and innovation toward sustainability.
4. Six TWI2050 Transformations are a framework for how to achieve the 2030 Agenda – jointly, they integrate all the SDGs and provide an entry point for achieving them.
5. Transformative governance is emerging – there is a growing understanding of governance needs for integrated SDG implementation.
6. Science, technology, and innovation are at the core of human progress – paradoxically, they have also brought about negative impacts, but they also provide solutions.
7. Granular, small-size innovations generally have faster adoption and diffusion – they can enable rapid change but require sustained investments.
8. The science-policy-society interface is essential for evidence-based transformations – research and development are enablers of sustainability-oriented innovations.
9. Transforming service-provisioning systems is necessary – improving human wellbeing and sharing resources fairly requires people-centered efficiency and sufficiency.
10. Transnational crises demand global context-sensitive responses – support of actors from local to international is key for accelerating reforms to achieve the sustainability transformation.