Transformations to Achieve the Sustainable Development Goals

Report prepared by
The World in 2050 initiative

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TWI2050 The World in 2050

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Foreword

The Industrial Revolution brought great progress to humanity. The global population increased sevenfold, life expectancy doubled, economic output increased a hundredfold and there are as many telephone connections as people in the world. However, many have been left behind. Some three billion people still do not have access to modern cooking and sanitation. A billion people go home hungry and do not have access to electricity, yet many of them have to charge their phones. Those left behind are the most vulnerable to the negative consequences of the Industrial Revolution, ranging from climate change to biodiversity loss.

Humanity is at a crossroads. Unbounded growth is endangering planetary support systems and increasing inequalities, the rich are getting richer and the poor even poorer. The transformation towards sustainable futures is an alternative possibility for people and the planet – a just and equitable world for all. This is exactly what the United Nations 2030 Agenda (adopted on 27 September 2015) offers and is thus a great gift to humanity. It presents a new social contract with its 17 Sustainable Development Goals (SDGs). It is an aspirational and ambitious vision for the future betterment of humanity and it gives strong reasoning for fact-based understanding of the interrelationships and synergies among the SDGs.

The World in 2050 (TWI2050) was established by the International Institute for Applied Systems Analysis (IIASA) to provide scientific foundations for the 2030 Agenda. It is based on the voluntary and collaborative effort of more than 60 authors from about 20 institutions, and some 100 independent experts from academia, business, government, intergovernmental and non-governmental organizations from all the regions of the world, who met three times at IIASA to develop pathways toward achieving the SDGs. Presentations of the TWI2050 approach and work have been shown at many international meetings including the United Nations Science, Technology and Innovation Forums and the United Nations High-level Political Forums. Two important meetings were held, one focusing on governance organized by the German Development Institute (DIE) in Bonn, Germany and the other on regional perspectives organized by the Stockholm Resilience Centre (SRC) held in Kigali, Rwanda.

This report examines the current trends and dynamics that promote and jeopardize the achievement of the SDGs. It presents the TWI2050 framework, the integrated pathways which harness the synergies and multiple benefits across SDGs, and approaches to governing this sustainability transformation. TWI2050 identifies six exemplary transformations which will allow achieving the SDGs and long-term sustainability to 2050 and beyond: i) Human capacity and demography; ii) Consumption and production; iii) Decarbonization and energy, iv) Food, biosphere and water; v) Smart cities and vi) Digital revolution. The report provides policy recommendations on how to achieve integrated pathways that implement these transformations.

Undertaking such a comprehensive initiative has required extraordinary leadership, intellectual input, support and coordination. Completion of this report has involved dedication and sustained contributions from many colleagues around the world. Special thanks and gratitude go to all contributing institutions that provided personal and institutional support throughout. The resources and the encouragement they provided helped make TWI2050 a reality. We are especially grateful for the contribution and support of the SRC, DIE and IIASA teams that have provided substantial in-kind support and vision needed to conduct an initiative of this magnitude. Special thanks go to my IIASA colleagues Sebastian Busch, Caroline Zimm and Pat Wagner for coordinating and managing TWI2050, to the Lead Authors for their leadership and guidance and all 60 authors without whose knowledge and dedication this report would not have been possible.

The publication of this report in July 2018 and its presentation at the United Nations High-level Political Forum is timely. TWI2050 shows that a transformation toward the sustainable future is possible with strong political commitment. It is my belief that this report will provide policy and decision makers around the world with invaluable new knowledge to inform action and commitment towards achieving the SDGs. I hope it will be a roadmap toward a sustainable future along integrated pathways and will divert from the alternatives that transcend the planetary boundaries and leave billions behind.

Nebojsa Nakicenovic
TWI2050 Executive Director

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Key Messages

1. **Transformation towards a sustainable future is possible but ambitious action is needed now!** The world and almost all regions are currently off course from achieving the Sustainable Development Goals (SDGs). Yet with bold and appropriate changes in values and deployment of policy instruments, the world can be steered towards achieving the SDGs by 2030 and providing a just and equitable future for all on a stable and resilient planet. These changes need to be based on the fact that sustainable development is a societal as well as an environmental challenge. The key is to invest in future priorities such as high-quality schools, improved health systems, efficiency and zero-carbon energy, environmental conservation and restoration, better food systems, more sustainable lifestyles, good governance institutions, and global cooperation initiatives to leverage dynamics towards the implementation of the SDGs. The World in 2050 (TWI2050) shows how to bring about six key transformations that will raise living standards, promote jobs, ensure social inclusion, and protect the natural environment, in short, to achieve "the future we want."

2. **Six transformations are necessary to achieve the SDGs!** 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 and demography; ii) Consumption and production; iii) Decarbonization and energy; iv) Food, biosphere and water; v) Smart cities; and vi) Digital revolution. Together they give a people-and-planet-centered perspective for building local, national and global societies and economies which secure wealth creation, poverty reduction, fair distribution and inclusiveness necessary for human prosperity while safeguarding the Earth system.

3. **Attaining the SDGs in a resilient and lasting way, requires vigorous action now, and a people and planet focus beyond 2030!** While the 2030 Agenda provides a visionary new social contract for the world, the ambitious and aspirational SDGs are necessary but not sufficient to lead humanity towards long-term sustainable development. In the globalized era we now live in, with rising social and political turbulence and pressures on the planet, sustainable development must fully integrate people and planet across scales, and can today be defined as attaining human prosperity and social inclusion within a stable and resilient Earth system. Processes that regulate the stability of the Earth system, from climate to water and ecosystems, are subject to longer-term and potentially abrupt changes. Diffusion of new infrastructure and major changes in human populations often occur on time scales of many decades. This warrants a timeframe until mid-century and beyond. Although achieving the SDGs by 2030 will be a difficult transformative process, many SDG targets will have to be revisited to adjust their ambition level with regard to longer-term socio-economic and environmental sustainability.

4. **As everything is integrated in the connected world, the grand transformation requires a holistic perspective!** The 2030 Agenda is holistic with deep and complex interactions across the SDG domains. The 17 SDGs are integrated and complementary and need to be addressed in unison. Focusing on individual or selected SDGs – be this during policy analysis or implementation – comes with the danger of adverse side effects related to other SDG domains or missing out on potential synergies and resulting multiple co-benefits. A holistic perspective helps to prevent lock-ins and mobilizes opportunities to accelerate and leverage the transformation towards sustainable development. It also enables the exploration of multiple possible implementation pathways. There are a myriad of pathways to achieve sustainable development that may differ along multiple branching points describing different development characteristics such as technological and behaviour change, economic and cultural transformations, transnational and unilateral governance, local implementation and global initiatives.

5. **Transformational change is needed but to succeed we must take along winners and losers!** Only with transformational changes will humanity be able to close the sustainable development gaps. But such deep change can be a double-edged sword – changes will imply winners and losers as history tells. The invention of the steam 'age' brought enormous positive economic benefit but also unheralded negative societal and environmental impacts. Understanding and analyzing the potential impacts, synergies and tradeoffs of the required transformations for achieving the 2030 Agenda will be essential. Likewise, it will be important to focus on and align the possible interest of different societal groups with respect to these changes and ensure that many of these groups promote the transformation. Transformational change must include ways to protect and provide opportunities for those who might otherwise be left behind and involve those who might encounter losses as a result of the changes. Transformation and justice are mutually interdependent.

6. **The world is at crossroads as we are currently experiencing signs of a counter-transformation!** A new wave of nationalism, populism, ethnic awareness, and loss of values is emerging in many countries around the world. People feel threatened by accelerating change, driven by globalization, digitalization, and also the sustainable development transformation. We need to build positive narratives oriented towards the future, human centered visions on local, national, and global levels. We need

significant investments in social cohesion and robust transformative alliances to enable transformational changes towards 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.

7. **A central element of the sustainability transformation is effective and inclusive governance!** Current governance models and arrangements, whether global, regional, national or institutional, are ill-suited to develop, oversee or implement truly integrated, multi-dimensional sustainable development agendas such as proposed by the SDGs. The transformation to sustainable development will require profound normative, societal, political and institutional changes. Such deep structural change is fundamental to achieving all the SDGs. Key elements include investments in capable public institutions, active civil societies, sustainability oriented alliances, science, engineering, the private sector and governments, and the formulation of plans and roadmaps to achieve the SDGs and long-term sustainability goals.

8. **Think globally, act locally! Think long-term, act now! It is all a matter of scale!** The 2030 Agenda is a global compact that will be implemented across multiple scales from transnational agreements, regional and national agreements and policies, down through individual municipalities, to the operations of public and private institutions, and individuals. The applicability and priority of individual SDGs will differ across geographies. It requires a culture of global cooperation and strong and growing alliances to protect and further develop a rule based global order. To leave no one behind globally, to protect the planet, and to develop multiple sustainable development pathways across scales are key ingredients to shape a peaceful future between our highly interdependent societies.

Box 1. The six transformations necessary to achieve the SDGs.

- **Substantial advances in human capacity are needed through further improvements of education and health care.** Education and health 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 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 saving potentials at different stages of the supply chain.
- **It is possible to decarbonize the energy system while providing clean and affordable energy for all.** Pathway analysis shows that energy-efficiency, increasing the share of renewable energy, electrification and carbon-capture and storage all play a key role in 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 towards 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 human dignity.

Transformations for Sustainable Development: A Synthesis

Jeff Sachs, Nebojsa Nakicenovic, Dirk Messner, Johan Rockström, Guido Schmidt-Traub, Sebastian Busch, Geoff Clarke, Owen Gaffney, Elmar Kriegler, Peter Kolp, Julia Leininger, Keywan Riahi, Sander van der Leeuw, Detlef van Vuuren, Caroline Zimm

Introduction

On 25 September 2015, all 193 United Nations (UN) Member States unanimously adopted the *2030 Agenda for Sustainable Development* with the 17 Sustainable Development Goals (SDGs) (UN, 2015b), which placed *sustainable development* as the core principle of global cooperation and national development. The 2030 Agenda provides an aspirational narrative for the desired future for human development together with an actionable agenda to be achieved by 2030. It specifies far-reaching time-bound, often quantified, objectives based on the most comprehensive consultation held so far among nations. For the first time, a world development agenda is adopted that integrates wide-ranging and aspirational goals for inclusive social and economic development, to occur within global environmental targets for oceans, freshwater, biodiversity, and climate, i.e., essentially a roadmap for redefining sustainable development as a people and planet agenda for achieving a prosperous and fair world within planetary boundaries. The Paris Agreement adopted a few weeks later (12 December 2015) reiterated the basic objective of sustainable development and established an agreed upper limit for human-induced global warming to "well below 2°C" and "pursuing efforts to limit the temperature increase to 1.5°C" (UNFCCC, 2015). The Addis Ababa Action Agenda adopted a few months earlier (16 July 2016) provided a new global framework for financing 2030 Agenda and emphasized the importance of science, technology and innovation for achieving the SDGs (UN, 2015a).

The World in 2050 (TWI2050) initiative endeavors to demonstrate how the objectives of sustainable development within planetary boundaries can be met, ensuring prosperity, social inclusion, and good governance for all. TWI2050 is a global research initiative launched by the International Institute for Applied Systems Analysis (IIASA), the Sustainable Development Solutions Network (SDSN), and the Stockholm Resilience Centre (SRC). The initiative brings together a network of more than 150 participants that includes leading policymakers, analysts, modeling and analytical teams from 60 organizations from around the world to collaborate in developing pathways toward sustainable futures and the policy frameworks needed for implementing the SDGs, and more importantly, for achieving the needed transformational change.

This report of the international TWI2050 scientific initiative was prepared by more than 60 authors and 20 organization and was launched at UN High-level Political Forum, 9-18 July 2018.

Major pillars of sustainable development

The UN member states define sustainable development as a world in which all nations enjoy economic prosperity, achieve social inclusion, and ensure environmental sustainability. These economic, social, and environmental goals are sometimes called the 'triple bottom line'. The 2030 Agenda underscores that human, economic, social, and environmental development must be underpinned by good governance and global cooperation, often called the fourth pillar of sustainable development. Each of the 17 SDGs contributes to these four dimensions, *viz* prosperity, social inclusion, environmental sustainability, and good governance.

These SDGs are 'universal', in the sense that they apply to all nations, and to all people within those nations. They are also 'holistic', in that all 17 SDGs must be achieved in unison. In the oft-repeated language of the 2030 Agenda, no one (and no nation or region or SDG) should be left behind. The 17 SDGs are a great gift to humanity and creating a new 'social contract' for the world.

The universality of the SDGs is unique not only in terms of establishing a moral standard for social inclusion and the right to decent lives for all, but also in underscoring the obligation of all nations to collaborate to meet global environmental targets, such as the "well below 2°C limit" in the Paris Agreement. Because human activity has already exploited many sustainable limits (such as extensive land use that gravely threatens biodiversity, and greenhouse gas concentrations that threaten climate stability) and have thus transcended planetary boundaries, all countries must deliver their share of global responsibility to achieve globally agreed environmental targets.

The SDGs are also interconnected and interdependent as many of them contribute to several dimensions of sustainable development:

Prosperity means that basic needs are met for all and includes SDG 1 (end of poverty), SDG 2 (end of hunger), SDG 3 (health for all), SDG 4 (education for all), SDG 6 (water and sanitation for all), SDG 7 (modern energy for all), SDG 8 (decent jobs for all), and SDG 9 (modern infrastructure for all).

Social inclusion means that all members of society have an opportunity to flourish, and includes SDG 5 (gender equality), SDG 10 (reducing inequality), and SDG 16 (freedom from violence).

Environmental sustainability means that the climate system is stable, biodiversity is conserved, ecosystems function well, freshwater is secured, rural and urban settlements are protected from pollution and are resilient to climate shocks, and includes SDG 6 (freshwater supply), SDG 11 (sustainable cities), SDG 12 (sustainable production and consumption), SDG 13 (climate safety), SDG 14 (conserving marine ecosystems), and SDG 15 (conserving terrestrial ecosystems), and implicit in many other SDGs, such as SDG 2, which stipulates the end of hunger and therefore depends on sustainable agriculture.

Good governance puts the interaction of state and non-state actors at the center of policymaking. While good governance implies that governments are following the rule of law, are accountable to their citizens and administer justice in a fair manner, non-state organizations are proactively involved and part of the governance system. Consequently, they cooperate with other countries. Good Governance is at the core of SDG 16 (rule of law, absence of corruption) and SDG 17 (global cooperation and partnerships for the SDGs) and explicitly addressed in other SDGs such as 10 on social and political equality or 5 on gender equality. SDG 16 is not only a goal in itself but also an enabler for other SDGs. Good and inclusive governance is thus seen as a precondition for combining and aligning visions of local, national, and global common welfare.

Each of the 17 SDGs contributes to the four dimensions of prosperity, social inclusion, environmental sustainability, and good governance (local to global).

Why TWI2050 is needed

The urgent question is how to act on this aspirational 2030 Agenda and to have a clear understanding of the full consequences, costs of inaction and the benefits of achieving the SDGs globally. As the SDGs are universal, and need to be achieved in unison, attaining them by 2030 requires deep transformation at all scales, from local to global and across all areas of human activity, while simultaneously reducing pressures on the Earth systems. It also requires new social values and norms as well as changes in individual belief systems that shape attitudes and behaviors toward achieving a sustainable future for all.

TWI2050 is a first attempt of exploring transformational pathways that take a comprehensive people and planet approach to attaining the SDGs within planetary boundaries – with a view of ensuring a prosperous and healthy future for all on a resilient and healthy planet. The 2030 Agenda is an essential part of this long-term transformation. The fundamental changes brought about by meeting the 2030 goals would need to extend through to 2050 and beyond to ensure a sustainable future for all and provision of stable Earth systems support for future generations. Today, no science-based pathways exist for successfully achieving all SDGs simultaneously. The global transformations necessary to achieve the SDGs urgently need a robust scientific foundation and fact-based way forward. TWI2050 is a global multi-year, multi-stakeholder, interdisciplinary research initiative designed to help address these issues. TWI2050 is a partnership between science and policy that aims to contribute to this understanding and to develop science-based transformational and equitable pathways to sustainable development. It aims at providing this information and guidance for policy makers and the wider public.

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

The TWI2050 framework (Figure 1) includes qualitative and quantitative elements and consists of the following: i) a broad transformational narrative (see Box 1), ii) targets and indicators for 2030, 2050 and beyond, and iii) specific sustainable development pathways (SDPs) for six key domains that include quantitative elements based on modeling approaches and complementary storylines. The key domains are:

- Human capacity and demography
- Consumption and production
- Decarbonization and energy
- Food, biosphere and water
- Smart cities
- Digital revolution

There can be many alternative pathways that explore branching points, lock-ins, resilience, inclusiveness, cooperation and differing transformational dynamics. The TWI2050 framework is designed to allow modeling and analytical groups (Integrated Assessment modelers, Earth system modelers and others) to identify and explore a portfolio of measures needed to achieve all SDGs jointly accounting for synergies and trade-off. With such common goals, and in some cases agreed common assumptions, the framework facilitates inter-comparison of results. This report presents of a number of exemplary sustainable pathways derived from recent analyses such as the Shared Socioeconomic

Pathways (SSPs)[1](Riahi et al., 2017). These pathways provide the basis for the fully integrated SDPs that will be developed in the next phase of the initiative.

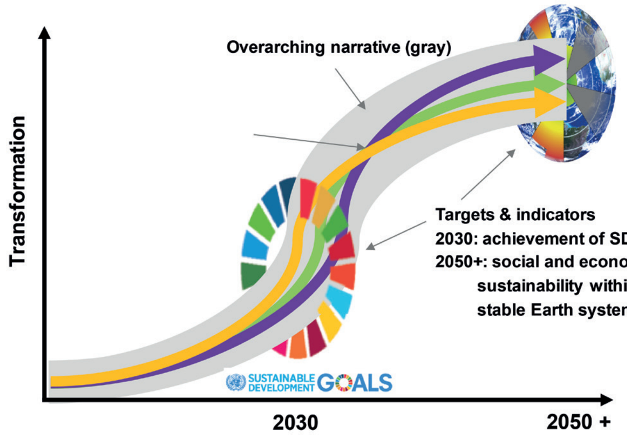

Figure 1. An illustration of TWI2050 conceptual framework. Two sets of science-based, normative targets provide bounds for the transformation toward sustainable future. The first are symbolized by the SDGs for 2030 and the second for 2050 and beyond symbolizes the achievement just and equitable future for all on a resilient planet. The gray band illustrates the overarching narrative that indicates how the future is connected to the present. It is about what needs to change to achieve the transformation toward sustainability by 'backcasting' from the normative targets. Also shown are alternative SDPs that provide model-based quantifications of the transformational changes. They can be interpreted as alternative realizations of the overarching narrative. SDPs in this report are indicative and the next phase of TWI2050 will focus on more integrated pathways although some characteristics would remain to be qualitative such as justice and peace. Source: TWI2050.

At the center of the framework is the 'framing narrative' described in Box 1 (see also Chapter 1). This provides a 'backcasting' narrative within which SDPs can be explored. The framing narrative aims to serve as a tool to connect the broad global analysis of SDPs to regional and national perspectives. For example, what are the narratives in Africa, Asia, North and South America, Asia and Europe that might be combined to form a coherent global narrative? The boundary conditions defined by the TWI2050 narrative translate to a set of quantitative and qualitative (multidimensional, science-based) targets and indicators of desirable end-states. The exploration of pathways includes qualitative and quantitative analysis of governance mechanisms and dynamics of social change needed to implement the 2030 Agenda. A SDP describes a multidimensional trajectory of economic, social, and demographic change, together with a detailed description of the economic, political, and social instruments to support the trajectory towards the desired goal. TWI2050 follows a five-step process in undertaking such pathway development and analysis:

1. Description of a framing narrative about the transformation to sustainable futures
2. Identification of the transformations needed to achieve the SDG targets and beyond
3. Selection of economic, political and social instruments to promote the transformations
4. Quantification of the timing, technologies, and costs of the transformations
5. Identification of measures including public awareness, public deliberation, social activism, and democratic oversight of science and technology, to overcome obstacles to change

Box 1. TWI2050 overarching narrative.

Globally and rapidly, awareness grows that the universally adopted SDGs can only be achieved through an unprecedented transformation of the technologies, economies, and societies worldwide. Only through such a transformation, is it possible to achieve a world in 2050 that is characterized by prosperous, equitable, and inclusive societies safely operating within planetary boundaries. Support for such transformational change emerges from rising societal uneasiness of slow progress on environmental and societal concerns and linked to renewed impetus to meet international agreements. This plays a role at the very local scale, where seeds for transformative processes continue to grow - but also in key sectors such as finance.

As a result, driven by a growing awareness of the social, cultural, and economic costs of unilateral decision making at all levels, a new joint global cognitive and normative framework emerges that provides the necessary perspective to tackle the world's sustainability challenges. The outcome is unprecedented levels of inclusiveness and cooperation at all levels from local to global. Knowledge societies emerge worldwide with an emphasis on public goods such as science, technology, and global commons. Heterogeneity of values and norms among societal groups, including religion, and nations continue, but are generally better aligned with this new 'global identity' based on shared responsibilities and vision for a sustainable future. Inequality is greatly reduced within and between countries. The number of conflicts including violence and homicides fall rapidly, and the world enjoys extended periods of geopolitical and social stability.

This overall change in mindsets, values, and norms, coupled with more effective governance for long-term sustainability, facilitates deep simultaneous transformations within six interconnected domains while the 17 SDGs are universally adopted as the new social contract.

[1] The SSPs are based on five different development routes for societal trends: i.e. sustainable development (SSP1), global fragmentation (SSP3), strong inequality (SSP4), rapid economic growth based on a fossil-fuel intensive energy system (SSP5) and middle of the road developments (SSP2). Each of the SSPs has been elaborated in terms of a storyline and various quantifications using models. The sustainable development scenario (SSP1) combined with stringent climate policy can also be seen as an example of a scenario exploring the route towards a more sustainable world – but it should be noted that the SDGs were not targeted in its development.

World at crossroads

The universal and unanimously agreed goals of the 2030 Agenda were chosen for reasons of both hope and fear. The hope arises from the scientific and technological revolutions, resistance of democracy, freedom and effective governance already underway across a number of societies, which could enable us to achieve goals that were out of reach for previous generations, including the end of extreme poverty and hunger, and the feasibility of achieving decent and fulfilling lives for all. Hope also arises from a multitude of initiatives across the world to define prosperity in non-growth terms alone, preparing the way for the emergence of novel and sustainable lifestyles. It also draws inspiration from the experience of the Millennium Development Goals, which showed how global goals can motivate and enable massive improvements, as demonstrated by unprecedented progress in reducing child mortality and combating HIV/AIDS, tuberculosis, and malaria. Contrary to some perceptions, progress was accelerated in some of the poorest and most fragile countries in the world (McArthur et al., 2018).

The fear arises from the stark realization that the world is currently not achieving sustainable development. The world is falling short in all four dimensions. Some parts of the world are still trapped in extreme poverty. Some regions are suffering from growing gaps between the rich and poor. Many countries lack essential state and governance capacities. All regions of the planet are suffering from three human-induced calamities of environmental degradation: global warming; loss of biodiversity; and pollution of the air, soils, freshwater, and oceans. And in many regions and nations populist nationalistic politics undermines global cooperation. In just over three short years since the SDGs were universally adopted we have seen the emergence of an anti-immigrant and anti-globalization backlash and marginalization of science that may undermine the 2030 Agenda.

While all countries are committed in principle to achieving the 17 SDGs and the Paris Agreement, there remain considerable doubts as to whether the goals will actually be achieved and significant disagreements as to how this can be done. Some critics of the SDGs argue that the goals are simply out of reach, too idealistic and infeasible in practice. Others argue that economic growth guided by market forces will be sufficient to achieve the SDGs. Markets will solve all problems and that all that is needed is a bit of patience.

Based on rigorous analysis and modeling, we suggest our own viewpoint:

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 and the Paris Agreement. Success is a matter of choice rather than inevitability or infeasibility. Choice requires the deployment of economic, political, social instruments, technological and cultural innovations, and changes in lifestyles to bring about the needed transformational changes at every scale.

There is overwhelming scientific evidence showing that a prerequisite to achieve the aspirational socioeconomic goals agreed upon with the SDGs, is a transformation to world development on a stable and resilient planet. Humanity has entered a new geological Epoch, the Anthropocene, where humanity – one single species – constitutes the largest driver of environmental change on Earth. Global environmental risks are high and rising. We have transgressed several planetary boundaries that regulate the stability of the Earth system (Steffen et al., 2015; Rockström et al., 2009), 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.

It is therefore fundamental to consider the SDGs as a necessary but not sufficient milestone for global sustainable development. The human quest is to meet the SDGs by 2030, then continue meeting them for all citizens, in an increasingly populated and wealthy world by 2050 and beyond, and to do so within the safe operating space of a stable and resilient planet. In short, global sustainable development is a world that transforms to meet the SDGs within planetary boundaries. This will entail deep transformations of the world's societies. The global consultation among all nations (which gave us the SDGs) combined with the latest advancements in Earth system science (expressed, e.g., through the Intergovernmental Panel on Climate Change (IPCC) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES)), provides humanity, for the first time, with a clear road map for a desired, prosperous, equitable and environmentally sustainable future for people and planet. This defines an overarching goal of world development for 2030 and 2050. The TWI2050 framing narrative and SDPs indicate what needs to be done to achieve this goal. The grand challenge and opportunity is to explore and embark on the myriad transformational pathways necessary to achieve it. This is key, as the 12 years between now and 2030 and the 32 years between now and 2050 will be critical for global wellbeing, even for survival.

TWI2050 gathers the scientific community in dialog with decision makers and multiple stakeholders to analytically support the exploration of SDPs to attain the SDGs within planetary boundaries by 2050. The 17 SDGs and 169 targets define an integrated and universal framework for a trajectory towards global sustainability development by 2030. Extending these to 2050 and integrating them with scientific targets for a biophysical safe operating space on Earth, delineates pathways for global sustainable development this century.

To meet the SDGs within planetary boundaries by 2030 and 2050 will require major changes across all human activities, lifestyles and values, and cooperation from national to global scales. This said, we have identified six major transformations – encompassing human capacity and demography, sustainable consumption and production, decarbonization and energy, food, biosphere, water and oceans, smart cities, and digital revolution – that empirical evidence, global assessments and analyses, show are necessary and potentially sufficient to attain the SDGs on a sustainable planet.

We summarize the evidence on these pathways in four sections below: i) we describe the current trajectory of the world economy and major regions; ii) the six major transformations – encompassing human capacity and demography, consumption and production, decarbonization and energy, food, biosphere, and water, smart cities, and digital revolution – that are both necessary and sufficient to achieve sustainable development are presented. Together they are all needed to raise productivity, ensure social inclusion, protect the planet, and create the conditions for political stability, peace and cooperation within and between societies. iii) we describe the obstacles to implementing the SDGs, such as vested interests and the long-term and complex nature of the SDGs; iv) the economic, political and social instruments and transformative governance mechanisms that will be needed to achieve the deep changes towards sustainability are dealt with in the final section.

The current trajectory

The current economic, social, and environmental trajectory, at the global scale and within most regions of the world, follows an unsustainable development path. If we define a sustainable development trajectory as one that simultaneously achieves the three dimensions of economic prosperity, social inclusion, and environmental sustainability at a pace sufficient to achieve the quantified objectives of the SDGs for 2030 and 2050, then most of the world falls seriously short of SDG objectives in one or more dimensions.

We identify five major sustainable development challenges that are described by the SDGs.

First, many people are trapped in extreme poverty, especially in sub-Saharan Africa and parts of South Asia, South-East Asia and Latin America. The poverty is multidimensional and comprises income (SDG 1), hunger and malnutrition (SDG 2), lack of healthcare (SDGs 3), lack of education (4), and lack of access to basic infrastructures services (SDGs 6, 7, 8, and 9).

Second, many countries have high and rising inequalities of income, employment and social status. Inequality is covered in particular by SDGs 5 (gender equality), 10 (income inequalities), and 16 (peace and justice). In addition, inequalities in access to public services (e.g., SDGs 3 and 4) as well as infrastructure and basic needs (SDGs 6, 7, 8, 9) are both causes and outcomes of other kinds of inequalities.

Third, human activity is degrading the physical environment and the global commons, violating planetary boundaries and thereby putting the stability of Earth within a Holocene-like state at risk. Major environmental challenges include human-induced climate change (SDG 13), destruction of biodiversity and ecosystems in oceans and on land (SDG 14 and 15), deterioration of finite freshwater resources (SDG 6), and release of chemical pollutants, from heavy metals, micro-plastics, pesticides, nuclear waste to overload of reactive nitrogen and phosphorus, into the air, soil, and water (SDG 12).

Fourth, demographic stresses are arising from high fertility rates (mainly in sub-Saharan Africa and parts of the Middle-East), rapid urbanization (especially in Africa and parts of Asia) (SDG 11), and rapid aging (in high-income and upper-middle income countries). They are driven in parts by lack of education (SDG 4), insufficient access to sexual and reproductive health and high child mortality rates (SDG 3), as well as gender inequality (SDG 5).

Fifth, weak and bad governance, failing institutions, and a rise in nationalism (SDG 16) in many countries and regions, as well as intensifying international conflicts and eroding multilateral systems (SDG 17) are undermining the local, national and global capacities to implement the 2030 Agenda.

These challenges are driven by long-term, path dependent second-order dynamics which are deeply embedded in our societal structures, have many feedback and anticipation loops among themselves and will prove extremely difficult to change. This requires us to change our perspective in order to understand and deal with the societal and socio-environmental dynamics involved. We need to view them in their full complexity. That perspective should focus on learning from the past, about the present, and for the future! At any time in the past (and the present), there were options among the directions that system dynamics could take. Some of these were adopted, others were not. We are not at crossroads where we need to adopt the right options – this requires proactive and anticipatory planning!

One of the main reasons the world is not on track towards achieving the SDGs is that sustainable development is not a self-organizing property of market-based economic systems. Market-based economic growth alone is rarely socially inclusive and environmentally sustainable. Without countervailing policies, markets are often reasonably efficient but also highly unfair, making the rich richer and the poor poorer. Moreover, producers and consumers rarely have the incentive to protect the air, water, soils, and climate, since most of the damage they cause is incurred by others, including future generations, rather than by themselves. Markets underprovide so-called public goods like infrastructure and protection of the global commons (the environmental systems and processes on Earth, e.g., the climate system, oceans, forest biomes, glaciers, clean air) that all citizens share and depend on for local environmental stability and provision of services, and they undersupply so-called merit goods such as health and education, which should be accessible to all people irrespective of income or social status, thus driving greater economic prosperity.

Because markets underprovide public goods, governments (and to a lesser extent, civil society) must provide them. The challenge therefore is to re-embed markets and shape them towards the sustainability goals. But governments often also fail to provide public goods. Sometimes they are too poor to provide them unless they benefit from development cooperation. Sometimes they are not competent to provide them. Sometimes the global good must be protected by many or all governments, because the problem is truly global in nature (as with most global commons such as climate change). And often the government is not motivated to protect the global good, perhaps because the time horizon of politicians is too short, or perhaps because the government is financially corrupt and therefore not interested in the true wellbeing of the population. These are all reasons why good governance and global cooperation are vital to achieving sustainable development.

Transformations to sustainable development

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

In view of the complexity and breadth of the changes occurring, and those to be expected, it is essential that we begin an effort to move beyond the sectoral and fragmented approach much sustainability research has followed thus far. Rather than investigate the role of water, or food, or energy, or even the water-food-energy nexus, we should design an approach that truly integrates all possible domains affected, focuses on tradeoffs and co-benefits and generally takes a holistic perspective that is at the core of 2030 Agenda. Another synergetic approach of the 2030 Agenda strives to harness science, technology, and innovation (STI) to accelerate progress. The holistic approach implies that the full complexity of the dynamics involved in each domain of social, social-environmental, and social-environmental-technological interaction – from the basic values and world view of individual societies and cultures, to their ways of interacting, their institutions, their governance, and so forth – will play out and impact on every aspect of present and future societies.

To move in that direction (at least for the moment as we are not able to deal with the full complexity of the total systems involved), we have selected to focus on the following six exemplary transformations that capture much of the global, regional, and local dynamics and thus encompass major drivers of future changes:

- Human capacity and demography
- Consumption and production
- Decarbonization and energy
- Food, biosphere, and water
- Smart cities
- Digital revolution

Arguably, the six transformations are necessary to achieve the SDGs by 2030 and to 2050 and beyond. Each transformation will require Herculean governance efforts and imply deep societal, cultural, and normative dynamics of change that we analyze in Chapter 4.

The six transformations are not intended to be a new clustering of the 17 SDGs nor to be a 'reduced form' of the SDGs and their 169 targets, but rather to describe systemic and integrative changes that are related to all SDGs as illustrated in Figure 2. Furthermore, they are central to the six SDGs reviewed at 2018 HLPF (SDGs 6, 7, 11, 12, and 15 as well as progress on 17). Arguably, they are not merely interlinked and interdependent with all SDGs, but also at the center of the great transformation toward sustainability and fundamental in 'turning the tide' of change.

Figure 2. TWI2030 focuses on six transformations that capture much of the global, regional, and local dynamics and encompass major drivers of future changes: i) Human capacity and demography; ii) Consumption and production; iii) Decarbonization and energy; iv) Food, biosphere and water; v) Smart cities; and vi) Digital revolution. Together they give 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 the SDGs if addressed holistically in unison. Source: TWI2050.

Why these six transformations?

Foremost, the six exemplary transformations give a people centered perspective: building local, national and global societies and economies which secure wealth creation, poverty reduction, fair distribution and inclusiveness are necessary for human prosperity in any society and any region of the world. While these objectives may be pursued differently in different contexts, there are some domains of action which appear to be universal including: i) institutions to enable and improve human capacities and capabilities, demography that includes secondary and not just primary education, adequate access to health care, fair labor markets, universal rule of law and means for managing aging societies; ii) essential and strategic infrastructure of any local, national, global economy and society such as energy, food systems, cities, settlements and mobility systems; iii) production and consumption systems where deep transformations need to take place to create wealth and ensure a good work-life balance, aiming at leaving no one behind and iv) STI that are essential for further progress toward achieving the SDGs. This is the paradox as STI has, in the past, created many negative externalities like transgression of planetary boundaries, but it is also indispensable for the transformation toward sustainability.

Progress on the SDGs will be facilitated if we can build and implement detailed STI roadmaps at levels that range from local to global (Colglazier). This is central as STI drives all SDGs and one of the most fundamental disruptive changes in human history – the digital revolution which puts comprehensive artificial intelligence at the center. A major challenge will be how to use the transformative nature of digitalization to create wealthy and inclusive economies and societies.

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

Putting governance, values and policy tools into the center

It becomes very clear, that the six major transformations require governance structures and capabilities, political action and the formation of actors of change on local, national and global levels. Taking the 2030 Agenda seriously implies that, incremental change is no option, transformative governance is needed. Transformations to sustainability are likely to be disruptive and, thus, could even trigger violent conflict. Throughout history, most great transformations were accompanied by violent conflict, including war (Osterhammel, 2010). Although a peaceful transformation to sustainability is the role model for the 2030 Agenda as TWI2050 we need to consider scenarios, which consider potential outbreaks of conflictive dynamics.

Governance and peace are two sides of the one coin. If states fail to govern, peace is at stake. The six transformations to sustainability require profound governance changes that are likely to challenge existing power constellations, create uncertainties and thus foster instability. Strong political institutions are thus crucial but they will only be effective for an integrated and peaceful implementation of the 2030 Agenda if they are able to accommodate the disperse distribution of power, multiple centers of authority and competitive relationships that characterize policymaking between the state, market and society in a multi-polar world (Fukuyama, 2004). Democratic oversight will be needed to govern the six transformations in an inclusive way.

The most likely constellations of state fragility show how the macro-political starting points for implementing the 2030 Agenda vary across regions from dysfunctional states to states with low levels of state capacity, legitimacy or authority (see Chapter 4). We emphasize therefore the importance of linking pathway-analysis with governance considerations. Investing in governance capacities and capabilities, building alliances for the great transformations towards sustainability, triggering mental mind shifts towards the 2030 Agenda, creating cornerstones of a global culture of cooperation and developing multiple, attractive. Context specific narratives on sustainability futures are becoming imperatives and preconditions for moving towards sustainable pathways at local, national and global levels (Chapter 4).

The 2030 Agenda (in contrast to the Millennium Development Goals (MDGs)) puts the people centered approach into planetary, Earth system perspectives. What does this imply for the six major transformations? We argue that the six transformation arenas remain the same. However, the goal systems in each of the six transformation arenas change profoundly. Instead of optimizing transformations processes 'only' towards traditional people centered development goals (growth, wealth creation, poverty reduction, reducing inequalities), sustainable development transformations now need to accept the local and global boundaries of the Earth`s system, to avoid planetary tipping points which would threaten human wellbeing and even human civilization.

This leads to the conclusion that implementing the 2030 Agenda requires a systematic alignment of people centered policies with strategies reducing and eliminating greenhouse gas and other emissions, managing local and global resource flows in a sustainable way, and avoiding pressures on ecosystems which might trigger unmanageable tipping points in the Earth system.

Thus, for the first time in human history, in the Anthropocene humans need to take responsibility to stabilize the planet itself– a civilizational shift in perspective is required. The transformations to sustainability therefore create not only economic, technological, social, and governance challenges, but also an imperative for deep cultural innovations.

We symbolized the potentially dual nature of the six transformations as being on the brink of the world at a crossroad. As argued above, the unanimously agreed SDGs were chosen for reasons of hope and fear. We demonstrate the gaps in all six exemplary transformations – between trajectories and pathways to inclusive sustainable development or counter transformation.

It is important to emphasize that the six major transformations need to take place in a very specific historical context**.**

Bifurcations

We argue that the implementation of the 2030 Agenda marks a major bifurcation in human history. The transformation towards sustainability is confronted with dynamics of speed, scale, and acceleration on many fronts: global population is on path to reach 9–10 billion people by 2050(Lutz et al., 2018); energy, food, and water demand could grow by up to 50% by midcentury (Riahi et al., 2017) if no significant departure from current trends occurs; urban population is likely to reach almost 70% in the same, short period of time (UNDESA, 2018) with associated expansion of urban infrastructure. The deep six transformations will require strategies, governance mechanisms, and adaptive capacities that enable our societies to cope with the described disruptive changes and to develop pathways towards sustainability.

The sustainability and 2030 Agenda oriented discourse still neglects, that there are two other major bifurcations in our societies and globally which are taking place in parallel.

First, the transformation towards sustainability coincides with an accelerating digital revolution, with artificial intelligence (AI) as its core driver, which astonishingly was not considered as a relevant trend in the 2030 Agenda. These innovations could enable the implementation of the SDGs, but also multiply already existing development problems (inequalities, power concentration, erosion of civil rights, erosion of governance capacities) and create a completely new generation of sustainable development challenges (Chapters 2 and 4): How could the digital innovations help to trigger the major six transformations early? How can we ensure that digital technologies and AI will be used to implement the 2030 Agenda, to improve the lives of the bottom 40 % of the global population, and to stabilize the planet? How will the AI revolution transform the global economy, trade patterns, global value chains and impact socioeconomic perspectives in the Global South? These issues are currently neither at the center of the debate about the digital age not at the center of sustainability and SDG oriented discourses. But we need to go even further. Beyond our comfort zones we need to start new debates about sustainability and the future of humans in the emerging Digital Age: How can we secure human control over semi-autonomous technical systems and AI? How would we like to shape the co-evolution of general purpose AI-driven technical systems and human civilization? Do we need normative guardrails for human enhancement and the emerging possibilities of deep transformations of humans based on technological innovations? We need to ask and discuss these questions now, in order to shape the digital future. The new challenge is, to learn to shape the digital revolution, and to align digital and sustainability transformations to implement the 2030 Agenda. We are entering the digital Anthropocene.

Secondly, the transformation towards sustainability and the digital revolution are coinciding with major changes and turbulence within our societies, regarding political and normative orders, and global power shifts. Right wing populism, narrow minded nationalism, xenophobia, hostility towards science, re-emerging 19th century power strategies threatening, instead of improving, a rule-based global governance system are gaining importance in many societies in both the Global North and the Global South, potentially undermining transformations towards sustainability. We should not ignore these counter-transformations.

We discuss the interdependencies of these three major bifurcations which our societies are confronted with, trying to present multiple pathways towards sustainability within turbulent local, national and global environments (see Chapter 4).

Six exemplary transformations

We consider each transformation in turn and emphasize from the outset that each transformation contributes to several SDGs.

Human capacity and demography

Human capacity promotes the wellbeing of individuals from birth to old age. Sustainable development policies should support, enable and empower each individual throughout their entire life from infancy and early childhood development to primary and secondary schooling, the transition from school to work, prosperous working years and leisure time, and high-quality years in old age and retirement. Achieving such results will require high-quality public infrastructure and services, and budgetary support for public investments, services, and transfers to vulnerable households.

The whole-of-life approach to human capacities should anticipate several demographic trends, including the transformation from rural to urban life, the increasing rates of technological change, the rising market demand for skills, the inequality of market earnings, the high participation of women in the labor force, the aging of the population and the low fertility rates and stable or declining populations.

In general, low-income countries today are characterized by predominantly rural populations; relatively low educational attainments and job skills; relatively low levers of technological change, relatively high inequality of market incomes; relatively low engagement of women in formal employment, and high participation in home production, smallholder farming, and self-employed market trade; large youth population and low median age; and fertility rates above replacement rates, and still relatively high child mortality despite recent progress.

By contrast, high-income countries are generally characterized by predominantly urban populations; high educational attainments; high rates of technological change, relatively low inequality of incomes based on extensive fiscal redistribution (though inequality has been rising and can be very high in some countries); high participation of women in formal employment; high and rising median age; and fertility rates at replacement rates or lower, leading to aging populations and associated health challenges of noncommunicable diseases. Medium-income countries lie between the low-income and high-income countries along these six demographic dimensions.

The transformation of human capacities and demography will entail the support for the transition to urbanized, high-skilled, high-employment, and aging populations, with low fertility rates leading to stable or declining populations (Figure 3). Major public investments in human capacities include universal health coverage (SDG 3), education (SDG 4), and basic infrastructure (water and sanitation, SDG 6; modern energy services, SDG 7; and transport and connectivity, SDG 9). The education process itself will have to empower young people to understand the nature of the sustainable development challenges and the kinds of global cooperation needed to achieve the globally agreed goals. Educational attainment is a major lever for fertility and mortality patterns (Figure 4).

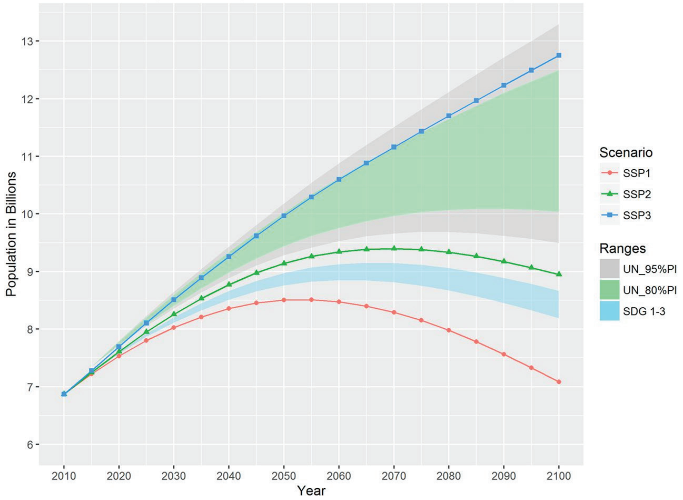

Figure 3. A range of future world populations is shown for three SSP pathways developed by the scientific communities for the Fifth Assessment Report of the IPCC. The population dynamics are based on the IIASA projections that range from a very high global population of almost 13 billion by the end of the century down to just 7 billion, a shade lower than the current population of 7.6 billion. The ranges are based on the probabilistic projections by the UN Population Division. While the range of global population by 2030 is relatively small from 8 to just over 9 billion, by 2050 it increases from about 8.5 to just over 10 billion. High populations are associated with lower rates of development together with high fertility while lowest ones are associated with high rates of development and low fertility. The later are also characterized by high levels of education attainment and health care and thus in line with the achievement of the SDGs. Source: Abel et al. (2016).

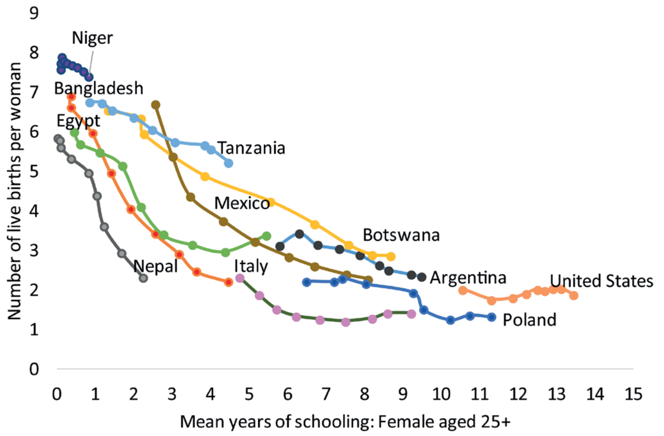

Figure 4. Number of live births per woman (1970-75 to 2010-2015) are shown as a function of women's educational attainment in years for select countries (1970 to 2010). At very low or no educational attainment, women have a larger number of children, ranging up to eight children per woman. In Italy and Poland, the fertility is now below the replacement level while in the United States it is just above. This indicates that the education of women is key for whether future populations will be big or small and thus also an important prerequisite for achieving sustainability in the world. Source: Education data from Barro and Lee (2013), fertility data from UNDESA (2017). Graphic courtesy of Raya Muttarak.

Sustainable pathways are characterized by gradually rising enrolment levels (Figure 5) such that by 2030 enrolment levels are achieved that lead to universal attainment of primary and secondary education levels for both boys and girls. High-quality education standards and education facilities are offered publicly, reflecting the public good nature of education. This is achieved through higher budget allocations and employment in the education sector and, where applicable, prioritizing official development assistance towards education. Sustainable pathways are also characterized by improved health outcomes. By 2030 a major reduction in premature, and causes, of deaths is achieved through the provision of universal preventive and curative medical care especially in low-income countries and with a specific focus on children. Advances in biomedical research aided by the digital revolution will allow for more targeted treatments of diseases leading to higher curative outcomes. Prevention of typical lifestyle diseases will benefit from higher levels of education and dietary changes. Overall health is a high priority with an emergent focus on 'mental and social' health, resulting in growth in economic output, employment, and increased life expectancy (Figure 6).

Advances in STI will lead to increased human knowledge and powerful knowledge-based systems and institutions leading to truly knowledge-based societies. For this to happen governments and institutions at all levels need to prepare for these advances and actively promote and support the relevant community.

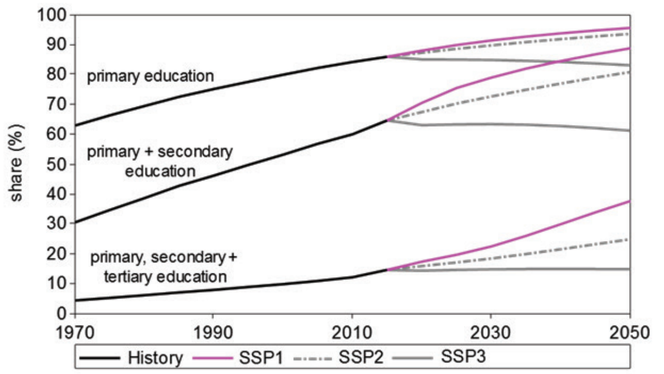

Figure 5. About 85% of global population over the age of 15 or some six billion people have primary education in the world, up from just over 70% in 1970. Three SSP projections are shown: SSP1 as an ambitious pathway and a proxy for an SDP, SSP2 and SSP3 as trend scenarios. In SSP1 and SSP2, the historical trend continues toward almost universal primary education, but the SDP calls for universal secondary education. SSP3 portrays no improvement at all. Secondary education attainment doubled form some 30 to 60% of people over 15 years of age. SSP1 portrays a significant acceleration reaching over 85% by midcentury. SSP3 portrays a deterioration leading to higher birth rates and population in the world. Most importantly, tertiary attainment increases in SSP1 and stagnates in SSP3. Even in SSP1 the midcentury level is just over 30% and not that much different from secondary education attainment in 1970. This is a huge challenge for the knowledge societies in times of digitalization. SDP would definitely need a higher educational attainment if no one should be left behind. Source: Data from Wittgenstein Centre for Demography and Global Human Capital (2015) and Lutz et al. (2018).

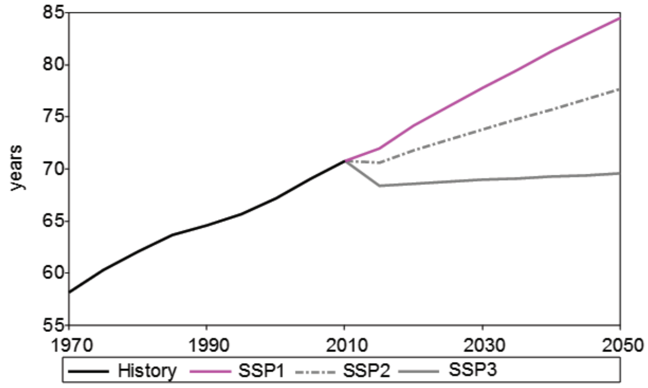

Figure 6. During the last century global average life expectancy doubled from some 35 to over 70 years. In the SSP1 pathway this development continues, reaching 85 years by midcentury. SSP1 characteristics are close to what is needed to achieve the SDGs and thus an important basis for the SDPs. SSP2 has significantly lower life expectancy while SSP3 portrays essentially no improvement at all. Source: Data from UNDESA (2017) and Wittgenstein Centre for Demography and Global Human Capital (2015).

Consumption and production

Today's consumption and production patterns lead to excessive use of natural resources through highly inefficient resource use (such as water, raw materials, wild catch from oceans, or land use) and generate unsustainable levels of pollution, including chemicals, plastics, nutrients, untreated sewage, and municipal waste. Unsustainable consumption and production patterns are one reason why countries around the world need to transform their energy systems, food systems, and cities. Inefficient resource use and poor waste management by industry and households are another challenge. To promote sustainable consumption and production patterns, we need to transform consumption and production patterns towards a circular economy.

The circular economy refers to the change of practices by businesses and households to ensure that both production and consumption behavior are consistent with environmental sustainability. A metaphor for the circular economy is that of a living cell that through efficient metabolism recycles many of the materials within the cell wall and reduces the exchange with the external environment. Ultimately, the circles of resource use will need to be closed to decouple human wellbeing from environmental resource use and pollution.

Consumption and production cuts across several of the other transitions, especially related to the resource-oriented and society-oriented SDGs, providing an ideal entry point for integrated pathway development. Across a variety of resources (energy, water, land, materials) end-use demand is the ultimate driver of current resource systems and associated improvements in efficiency and reductions in waste therefore offer the largest 'upstream' systems leverage effects. A key element of a transformation to sustainable consumption is the notion that wellbeing does not necessarily rely on the consumption of resources *per se* but is rather derived from the *services* and *amenities* these resources help providing. In particular the digital revolution offers huge potentials to make accessible these services in a much more resource efficient manner (Figure 7).

Figure 7. 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 smart phone 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 hundred times more power. Bundling of services from various devices in the smart phone can be seen as an example for the power of the digital revolution and the huge potential of increasing the resource efficiencies through new technologies and behaviors. Graphic courtesy of Nuno Bento based on data in Grubler et al. (2018) and visualization of Tupy (2012).

We have already mentioned several aspects of sustainable production practices in energy (efficiency in energy use, conversion from fossil fuels to renewable energy including renewable power-to-gas conversion, fuel switching), food and biosphere (dietary shift away from a high beef diet, more efficient fertilizer use, reduced food loss and waste), and cities (recycling of urban wastes, sewerage and wastewater treatment, urban planning for high-density agglomerations).

Other priorities for the transformation of consumption and production patterns include improvements in material efficiency and lower emissions, for example by reduction of iron ore with hydrogen, use and reuse of materials such as carbon, recycling and 'urban mining' to close the circle on the use of rare minerals. The shift towards a circular economy requires life-cycle approaches to products across a broad range of industrial value chains as well as human agglomerations, such as a large city.

Decarbonization and energy

The world requires universal access to modern energy services together with a decisive drop in CO_2 and other greenhouse gas emissions. Over a billion people do not have access to electricity and some three billion to clean cooking (IEA, 2017). This leads to about four million premature deaths, especially women and children who spend most time indoors (WHO, 2014). Universal access is essential for development and environmental sustainability. Positive effects on reduction of greenhouse emissions are likely due to better combustion and shift toward renewables, but far from sufficient at current rates of progress.

The climate science is clear. To have at least a two-thirds probability of remaining below 2°C global warming (above preindustrial levels) requires that the cumulative net emissions of CO_2 from 2011 onwards should not exceed 1,000 Gt (Gigatons) of CO_2 (Pachauri et al., 2014). Yet annual emissions from fossil-fuel combustion, industry and land-use change have been on the order of 40 $GtCO_2$ per year since 2011 (Le Quéré et al., 2018), meaning that humanity has roughly 18 years remaining of CO_2 emissions at the current global rate. Some recent studies (Goodwin et al., 2018; Millar et al., 2018; Tokarska and Gillett, 2018) indicate that the remaining budget could be slightly higher as less of it would have been used in the past. This however does not change any of the implications to succeed on two decisive global benchmarks: i) the global curve of CO_2 emissions from fossil-fuel burning and land-use change must turn steeply downwards in the next few years, and ii) by 2050 we should have largely transformed to a fossil-fuel-free world energy system (with a residual of remaining CO_2 emissions < 5 $GtCO_2$/year). To the energy-related emissions we need to add the emissions due to land-use change, considered below in the discussion on food and the biosphere. And to add to the drama, global CO_2 emissions due to energy use in the past years continued to rise as the world economy grows despite the relative decoupling between CO_2 emissions and GDP growth. This implies that the current trajectory with gradual decarbonization and efficiency improvements is in no way sufficient to reach the Paris Agreement.

It is therefore necessary to reduce energy-related greenhouse gas emissions dramatically and decarbonize the world's energy system by midcentury. The most plausible path is a phase-out of fossil fuels and their replacement by zero-carbon energy sources such as wind, solar, hydro, geothermal, ocean, nuclear (where it is politically and socially acceptable), and other potential sources. The options available to any particular location will depend on the local alternatives and the options for long-distance transport of zero-carbon energy carriers. Long-distance transport may include long-distance power transmission (for example, using high-voltage direct-current transmission to reduce transmission losses) and the conversion of zero-carbon energy into other forms such as hydrogen or synthetic hydrocarbons that can be transported in other ways (such as pipelines, ships, rail, etc.). Given the rapid speed required and relative difficulty and limited set of options for decarbonization in the heating and transport sectors also implies a gradual electrification of these sectors. While currents trends do not indicate that the world could embark on a trajectory of limiting global warming below 2°C, levers, that are so far hardly tapped, could still turn the tide, *viz.*, energy demand and distributed energy generation. Energy demand could be reduced drastically with the right incentives in place. For example, energy demands could be as much as 40% lower in 2050 relative to 2010 due to transformation towards efficient energy technologies and responsible consumption behavior (Grubler et al., 2018). Distributed energy generation, facilitated by the digital revolution, could lead to a much faster rate of decarbonization than experienced in the past. Recent developments and price dynamics suggest that we could be at the brink of such a revolution in the energy sector.

A sustainable pathway for the energy-system emissions therefore could be constructed as follows (Figure 8): Consider a phase-out path in which today's 40 Gt of CO_2 emissions are reduced to zero in a linear down-ramp to constrain cumulative emissions to about 700 $GtCO_2$. If the linear down-ramp starts in 2020, fossil-fuel based emissions would end in 2050, and would reach 20 Gt (that is, roughly half of current emissions) in the year 2035. If instead, there is a geometric decline, with emissions falling by half each decade (7% per year), emissions would reach 20 Gt by 2030, 10 Gt by 2040, 5 Gt by 2050 and then asymptotically to zero (Rockström et al., 2017).

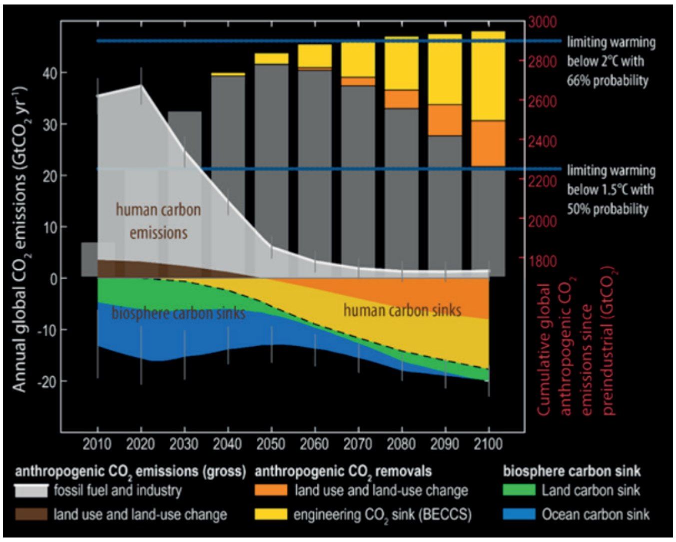

Figure 8. Cumulative and annual emissions and sinks of CO2 are shown for stabilizing global climate at below 2°C and 1.5oC. Most of carbon emissions shown in gray are energy-related. Together with land-use emissions they need to decline toward zero by midcentury. The figure is called "Carbon Law" as a metaphor to Moore's Law of semiconductors where a number of transistors on a chip doubled every 2.5 years. Carbon Law indicates that global emissions need to be halved every decade. In addition, human carbon sinks need to increase to almost half the magnitude of current positive emissions: A tall order. Carbon capture from biomass (BECCS) and land-use change are here the key. Third, biosphere carbon sinks need to be maintained as atmospheric concentrations decline. The vertical gray bars show cumulative emissions since the beginning of the industrial revolution of some 2,000 billion tons CO_2. This budget, or carbon endowment of humanity, will be exhausted shortly as the remaining emissions for achieving stabilization at below 1.5°C are essentially nil while we still emit some 40 billion tons CO_2 per year. Net-negative emissions are needed to stay within this budget. The remaining budget for stabilizing at 2°C is a bit more generous so that the demand on net-negative emissions can be significantly reduced. The Carbon Law can be seen as roadmap towards making the Paris Agreement and the SDGs a reality. Pathways shown in this report like the SSP1 variant focused at the 1.5°C target or the alternative scenarios portray similar dynamics whereas the latter is quite unique among stabilization pathways as it does not need net-negative emissions because of vigorous changes in end-use technologies and behaviors. Source: After Rockström et al. (2017).

Decarbonization brings multiple benefits by reducing energy-related pollution at all scales, including those from transport and industry, which are major drivers of (indoor and) urban PM2.5 pollution. Universal access to electrification based on renewable energy can eliminate indoor air pollution, which is a major cause of respiratory disease especially for children and women who spend much of their time indoors.

The various decarbonization scenarios suggested in recent studies (Figure 9) all point to the same overall strategy for the energy transformation. It comprises four pillars: i) energy efficiency, to reduce energy use per unit of economic output; ii) zero-carbon power, the shift of electricity generation from fossil fuels (coal, oil, and gas) to renewable sources; iii) electrification and fuel switching, the conversion of current uses of fossil fuels outside of power generation (such as the internal combustion engine; boiler and heaters in buildings; and various industrial processes such as steel production) to zero-carbon electricity and biofuel-based technologies – vehicles will shift from internal combustion engines to battery electric vehicles or hydrogen-based fuels; heaters will shift from boilers to electric heat pumps; biomass and recycling may replace fossil fuels in some industrial applications, and so forth; and iv) universal access for all and especially those excluded today to decarbonized, clean cooking and electricity.

The energy transformation would not be sufficient, however, to stay within the carbon budget as another 5-10 Gt per year of CO_2 emissions result from land use (farming, livestock) and land-use change (deforestation and conversion of grasslands to pastures). Moreover, many pathways towards decarbonizing energy systems project significant increases in bioenergy, which must be understood in the context of food security, biodiversity conservation, water use, nitrogen and phosphorus needs for fertilizers, and other constraints on sustainable land use and food systems. Thus, the energy transformation must be accompanied by a transformation of land use and food systems, as detailed in the next section.

Is the energy transformation feasible and affordable for the world and for every major region? The answer appears to be yes. Thanks to the rapidly falling costs of renewable power and improved technologies to tackle the four pillars of the energy transformation, several estimates of the cost of decarbonization suggest that the overall cost of transformation should be no more than 2.5% of GDP per year on average across the world. That suggests a price tag on the order of up to US$1 trillion per year (increasing gradually from about US$300 billion in the near term), a hefty but manageable sum. The US$1 trillion per year represents not the annual total investment in energy, which would be around more than two up to four times that amount (depending on pathway), but rather the incremental costs of moving to zero-carbon energy (McCollum et al., 2018). The latter paper has shown that the most important task is to align projected investment patterns better with sustainability goals. Improving energy security, eliminating air pollution and decarbonization at the same time brings multiple benefits and simultaneously reduces incremental investment costs (McCollum et al., 2013; Riahi et al., 2012).

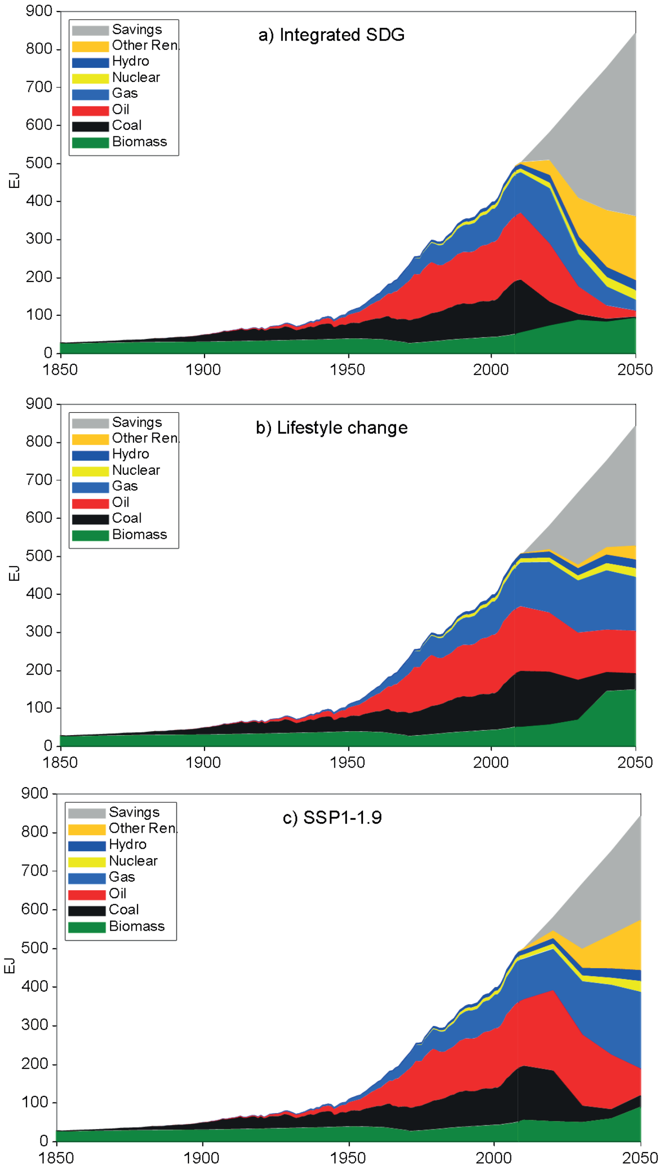

Figure 9. Historical evolution of the global primary energy is shown and in the three different pathways. a) Integrated SDG characterized by low demand, b) the lifestyle change scenario developed by IMAGE – implementing measures related to food and energy systems and lifestyle change and c) SSP1 1.9 scenario (a sustainability scenario achieving the 1.5°C target). Today, fossil sources provide about 80% of primary energy after two centuries of exponential increase of about 2% per year. Historically, there was a shift from traditional biomass to coal with the advent of seam, steel and railways and later to oil and gas with development of the internal combustion, electricity, chemicals and many other technologies. Integrated SDG pathway portrays almost complete decarbonization of energy by midcentury with small residual use of oil and gas. This is achieved through major changes in energy end use and behaviors. The second pathway is still relatively fossil-intensive by mid-century and relies on bioenergy with CCS in the second half of the century this could lead to conflicts with food production and preservation of biodiversity. In the scenario, this is mitigated via assumed changes in food waste, diets (less meat intensive) and yield increase. The SSP1 1.9 stabilizes climate change below 1.5oC requiring carbon capture and storage from natural gas and biomass. All pathways portray vigorous efficiency improvement compared to SSP2 baseline pathway; differences are shown in gray (savings). Source: a) "integrated SDG" from Parkinson et al. (2018), b) "lifestyle change" from van Vuuren et al. (2018), c) SSP1-1.9 from Rogelj et al. (2018), SSP Database (2012-2016).

Food, biosphere, and water

The third great transformation is in food systems and land use, while enhancing the resilience of other parts of the biosphere including water and oceans. The current patterns of land use, mainly related to the production of food, biofuels, and fiber, are unsustainable in three ways. First, today's agricultural systems (including livestock and aquaculture) are major contributors to human-induced climate change, unsustainable water use, poor health through inadequate nutrition, eutrophication through nutrient overload, air and water pollution, deforestation, and the loss of biodiversity. At the same time, agricultural systems and other forms of land use are vulnerable to the environmental changes now underway, through the increasing severity of droughts, floods, diseases, and land degradation caused, in part, by climate change. Similarly, most ocean and freshwater fisheries are overexploited, and oceans are exposed to high levels of pollution, including acidification from CO_2 in the atmosphere. Third, today's food systems do not deliver healthy diets with some 800 million people undernourished (FAO et al., 2017) and nearly 2 billion overweight (WHO, 2015). Taken together, transformations of land use and ocean management must reduce the human-induced damages caused by agriculture and the food system while also making agriculture more resilient to environmental changes now underway and ensuring healthy diets.

Consider first the many ways that agricultural systems and fisheries contribute to environmental degradation. Since the advent of agriculture some 10,000 years ago, humanity has transformed approximately 40% of the Earth's ice-free land surface into different forms of agriculture (rangelands and cropland) (Foley et al., 2011). This is the prime cause of the global mass extinction of species now underway and the transgression of the planetary boundaries on land use (which puts us at risks of destabilizing major biomes, such as forests). Agriculture and associated land-use changes are a major source of greenhouse gas emissions, by some measures the single largest source. Agricultural production results in several kinds of greenhouse gas emissions: CO_2 emissions directly linked to energy use in the farm sector (for example, farm machinery and the transport of food from farms to end-users), N_2O (nitrous oxide) emissions from nitrogen-based fertilizers, and CH_4 (methane) emissions from both livestock and rice production. Also, deforestation that results from the expansion of farmlands and ranchlands leads to the release of CO_2 from soils, vegetation, and tree cover, and reduces the capacity of the land sector to act as a sink for greenhouse gases. In addition to the environmental damage from land-use change and greenhouse gas emissions, farms and aquaculture also contribute to the loss of biodiversity through pollution from pesticides and chemical fertilizers; the introduction of invasive species; overhunting and overharvesting of plant and animal species; and soil degradation resulting from tillage and other farm practices. Aquaculture in particular accelerates unsustainable fishing practices through its use of wild catch as feed. Fisheries around the world are severely overexploited, and modern fishing practices, such as trawling, cause large-scale destruction of natural habitats – increasingly also in the deep seas.

Agricultural systems, fisheries, and the livelihoods that depend on them are highly vulnerable to the human-induced environmental changes now underway. Global warming will threaten food production in many regions, especially in the tropics and sub-tropics, as higher temperatures lower yields. Climate change will lower crop productivity through a greater frequency of extreme weather events, such as droughts, floods, and high-intensity storms. Freshwater scarcity will generally increase in today's dryland regions. Higher temperatures will mean higher rates of evapotranspiration and reduced soil moisture. Groundwater depletion will mean less freshwater availability in many of today's breadbaskets, such as the Gangetic Plains and north China plains, where millions of bore wells for crop irrigation are extracting water from aquifers much faster than recharge. Global warming also leads to the melting of glaciers in several regions (including the Alps, Andes, and Himalayas) that currently provide a continuous flow of freshwater for farms and households during spring and summer months. Human-induced changes in habitat (such as through deforestation and conversion of grasslands to pastures) reduces biodiversity and introduce invasive species that threaten agricultural production.

Similarly, global warming, ocean acidification, overfishing, and pollution of oceans and coastal ecosystems are threatening biodiversity and the livelihoods that depend on fisheries. Many of the world's fisheries are on the brink of collapse due to excess fishing. Almost 30% of fish stocks commercially fished are estimated to be over-fished, and nearly 60 % of the fish stocks are fully fished (FAO, 2016). The oceans are also burdened by acidification (due to atmospheric CO_2), eutrophication (due to the massive runoff of chemical fertilizers), and pollution, such as with micro-plastics that have entered marine food chains. Coastlines are especially vulnerable as they are hit by many human forcings, including drainage of wetlands, coastal over-development, destruction of mangrove forests, and of course multiple forms of pollution.

The implications are clear. The world will need a major transformation of agricultural systems and fisheries both to mitigate human-caused environmental degradation and to build resilience into agricultural production. There will be several dimensions of that transformation. One guiding principle will be the effective regulation of land use. To preserve biodiversity and ecosystem functions, some parts of the planet must become protected areas; the biologist E. O. Wilson has called for protecting "half Earth" (Wilson, 2016). There is mounting scientific support for such a transformative approach to safeguard ecological functions and resilience for all food production and the supply of ecosystem services. This provides support to the conclusion that the world has reached a juncture where feeding humanity (and attaining global sustainable development) must essentially occur on already transformed and existing agricultural land. This means safeguarding the remaining "half Earth" under natural forests and other ecosystems, for ecological functions and resilience, which in turn translates to a global sustainable agricultural revolution, providing more and healthier food through sustainable intensification on existing farm land, returning land to nature (Figure 10).

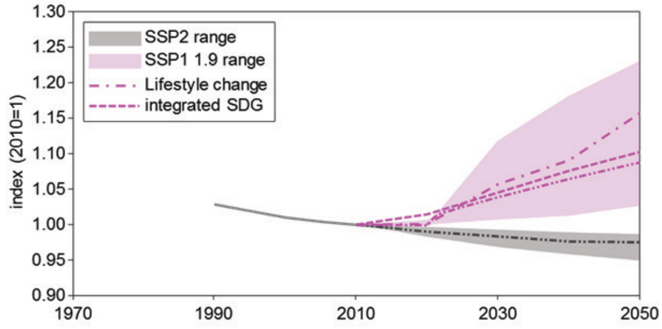

Figure 10. Global forest cover decreased to about 40 million square kilometers (4 billion hectares) and would continue to decrease in the SSP2. The opposite is the case in the other pathways toward sustainability where the forests increase because land is 'returned to nature'. However, the variation is very large. In the SSP1 1.9 range, the upper case is depicted by scenarios that implement land-saving practices such as higher, sustainable yields, reduction of food waste from production to use and changing dietary practices. Historical developments and those in the pathways are indexed at 2010 level so as to eliminate differences in data sources and across the models for the future. Source: "integrated SDG" from Parkinson et al. (2018), "lifestyle change" from van Vuuren et al. (2018), SSP1-1.9 from Rogelj et al. (2018), historic data from FAOSTAT (2018), SSP Database (2012-2016).

For land that is in agriculture use as croplands, pastures, and managed forests, this means modification of agricultural practices to minimize environmental damage and maximize resilience. Such practices include precision farming to economize on fertilizer and water use and to maximize yields (Figure 11); no-till farming to protect soil quality; agro-ecology to optimize the crop mix to sustain biodiversity and resist the dangers of pests and pathogens; and improved harvesting and storage practices to reduce post-harvest losses.

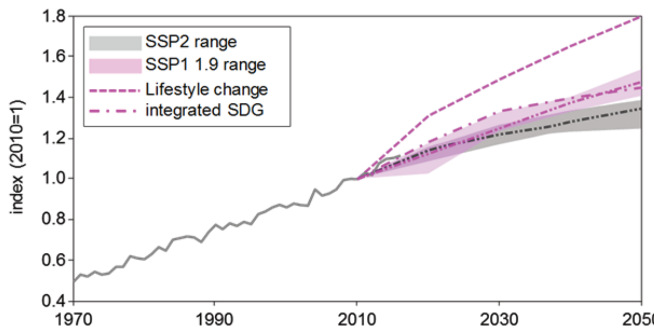

Figure 11. Yields continue to increase across all pathways in the figure including the SSPs ranging from a 50% to almost another doubling. The transformation to sustainability needs land-saving practices to leave "half Earth" to nature and at the same time mitigate environmental degradation and to build resilience into agricultural production systems. Historical developments and those in the pathways are indexed at 2010 level so as to eliminate differences in data sources and across the models in the base year. Source: "integrated SDG" from Parkinson et al. (2018), "lifestyle change" from van Vuuren et al. (2018), SSP1-1.9 from Rogelj et al. (2018), historic data from FAOSTAT (2018), SSP Database (2012-2016).

Similar considerations apply to ocean management. Fisheries practices around the world have so far failed to limit fishing to sustainable levels in most regions. Here too the ocean will need a variety of measures, including protected marine areas; restrictions on fish catches; crackdowns on illegal and undocumented fishing; reduced flows of chemical fertilizers to the sea; protected coastlines and wetlands; and others.

Yet another priority for action relates to diets and the loss and waste of food. Countries need to encourage healthier diets through public awareness campaigns, removal of subsidies for unhealthy and environmentally harmful production techniques, and careful management of land use, oceans, and other environmental resources. In countries with high beef consumption per person, reductions in beef consumption can promote human health while also protecting the environment. Beef has an especially adverse ecological burden because each kilogram of edible beef requires 10-15 kg of feed for the cattle. Similarly, some 30% of food is lost or wasted and does not reach the plate. Reducing food loss and food waste is one promising way to reduce the environmental pressure from, and vulnerability of, current food systems. Only about a half of the food yield ends being eaten (FAO, 2011).

Smart cities

Cities today are home to around 55% of humanity and 70% of global economic output. By 2050, urban populations are projected to account for around 70% (Figure 12) of humanity and perhaps 85% of global output (Jiang and O'Neill, 2017; UNDESA, 2017). What happens in cities, therefore, will determine the wellbeing of most of humanity and the prospects for sustainable development. For this reason the world's national governments adopted SDG 11 on sustainable cities to promote cities that are for people, are economically productive, socially inclusive, and environmentally sustainable. Unfortunately, most of the world's cities do not now pass the three-part test for sustainable development. A further complication is that most of the urban population lives in smaller to medium sized cities so that the transformation must occur simultaneously across all settlements and not merely in the mega conurbations like the Tokyo-Osaka corridor, Pearl River delta, or the Boston-Washington corridor of the US.

Many cities lack the basic urban infrastructure needed for economic productivity, social inclusion, and environmental sustainability. Informal cities and slums account for a quarter of the urban population. Most lack the basic amenities for fulfillment of fundamental needs like sanitation, electricity, clean heating and cooking fuels, education, mobility, security, and healthcare. Yet, urban infrastructure should include an efficient transport system; universal access to reliable and low-cost electricity, safe water and sewerage; recycling and other sustainable waste management; high-speed and low-cost broadband connectivity to support businesses and public service delivery. These should be deployed according to urban development plans that take account of future population growth. This is a tall order in any

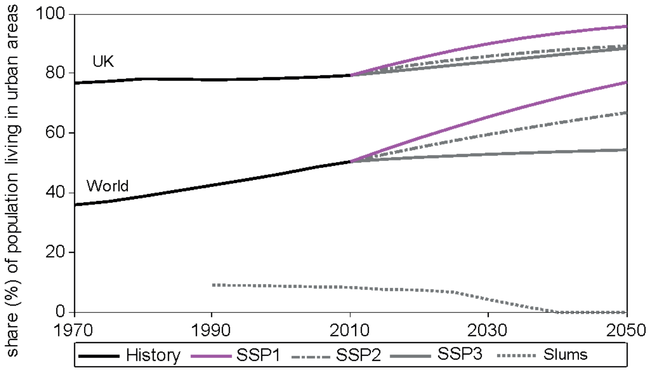

Figure 12. Urbanization is a very powerful force in human development. More than half of people or almost four billion already live in urban areas, most is small to medium sized cities and many in emerging urban corridors and agglomerations. The urbanization trend intensifies in the SSP1 while it stagnates. Past and projected global urbanization rate according to three SSP scenarios. Urbanization of United Kingdom is shown for comparison as representative of high-income countries where most of the people live in urban areas and only a few percent are left in rural settlements. The situation will be similar on the global level should the urbanization rates observed today prevail during this century. Source: Jiang and O'Neill (2017) and UN-Habitat (2016), SSP Database (2012-2016).

city, but particularly in informal settlements with a lack of urban planning and investment capabilities.

Many cities also lack policies to ensure social inclusion. Cities are often strongly sorted between rich and poor, by ethnicity, or both. Public services such as transport, health, education, water, and sanitation may be deficient or even non-existent in the poorer areas. The poor may have little access to decent jobs because of large distances involved in commuting and other restrictions to job creation.

Yet perhaps most shocking are the hazardous environmental conditions and the vulnerability to disasters afflicting hundreds of millions of urban dwellers in the large cities of the developing world. Many of these cities are chronically burdened by high air pollution, such as particulate matter (e.g., PM2.5) that is several times higher than the limits specified by the World Health Organization (WHO). The air pollution results from a combination of vehicular emissions, fossil-fuel burning in power plants and factories, coal use in homes, pollutants from heavy industry, and the burning of crop residues. The WHO estimates that air pollution is implicated in the premature deaths of millions of people each year. Often the water supplies are no better, with untreated household sewerage and toxic pollutants released into the waterways. Climate change adds enormously to the urban environmental stresses, by causing heat waves, droughts, increased transmission of urban vector-borne diseases such as dengue fever, and extreme precipitation, high-intensity tropical cyclones and flooding. Both environmental degradation and vulnerability to disasters exacerbate inequalities and exclusion since poorer neighborhoods tend to be affected more severely.

At the same time, half of the global CO_2 emissions from energy use are emanating from the vehicles, factories, commercial buildings and homes of the world's cities. Cities vary in their CO_2 emissions per capita according to density. High-density cities with public transport and walking areas (e.g., Barcelona) emit far low emissions per capita than low-density sprawling cities that rely on private automobile use for most transportation (e.g., Atlanta).

The transformation to sustainable cities requires an integrated set of actions, city by city, around the world. While urbanization processes evolve in a very specific context, and thus challenges may vary significantly, we can suggest some components that we think should be integral to any city in the world. SDP are characterized by high connectivity and 'smartness'. The digital revolution and the availability of autonomous, high-speed transport options change the nature of urbanization with more people able to connect to the dynamism and services offered by cities in more remote locations, leading to increased integration of the urban hinterland. The emergence of polycentric, high-density-urban-rural landscapes in conjunction with the digital revolution facilitates the rapid uptake of cleaner, smarter and decentralized technologies and production processes such that cities overall are becoming more self-sufficient, less polluting, and circular in terms of resource consumption. The backbone of every well planned, functioning city is a reliable, low-carbon infrastructure including low-carbon electricity, electric-powered public transportation, electric light-duty vehicles, electric heating and cooking, efficient road networks, broadband connectivity, and water, sanitation and sewerage, accessible to every inhabitant of the city. Equally, high-quality public services, including healthcare, education, and utilities (power, water, connectivity), security that are universally accessible and affordable are a necessity. Further characteristics that define cities in the TWI2050 integrated pathway are inclusiveness, access to open spaces (incl. green areas) and a high level of social interaction. This is achieved *inter alia* through a paradigm shift in housing policies, that no longer lead to segregation by class or race and where housing is no longer considered a purely private shelter but is an essential component of a larger social system giving people better opportunities to connect with each other thus reducing 'urban anonymity'. The key competence required in this regard is urban planning and design which respect the rights of all city dwellers and enable basic drivers of human wellbeing such as security, trust, local identities, lively neighborhoods and participatory approaches.

Digital revolution

Perhaps the greatest single enabler of sustainable development in the coming years would be the digital revolution, constituted by ongoing advances in AI, connectivity, digitization of information, additive manufacturing (3D printing), virtual reality, Internet of things (IoT), machine learning, block chain, robotics, quantum computing and synthetic biology. The digital revolution rivals the steam engine, internal combustion engine, and electrification for the pervasive effects on all parts of the economy and society. It has been made possible by an interconnected set of discoveries and inventions, including semiconductors, logic gates, computer architecture, integrated circuits, microprocessors, packet switching, the Internet, mobile broadband, public-key cryptography, and global positioning system (GPS), among others. The pace of advance continues exponentially with imminent breakthrough prospects for AI, quantum computing, virtual reality, 5G broadband, and other technologies. As in the industrial revolution that initiated explosive development through the convergence of steel, steam and railways, coal and textile and other new manufacturing process, it was the convergence of these technologies, institutions, settlement patterns and lifestyles that generated the deep transformations. Likewise, the convergence of new digital technologies could be even more explosive with great winners and losers.

An enormous success among many development failures is that mobile phones reach four-fifths (World Bank, 2016) of the world's 7.6 billion people (UNDESA, 2017). This was fundamental in improving the lives of many including those previously excluded. Ironically, one billon phone owners do not have access to electricity! The mobile phone revolution may lead to 'leap-frogging' of the developing world ahead of the most industrialized countries with the diffusion of new services such as mobile money and more effective financial services for establishing businesses (Figure 13). At the same time, it is clear that the digital revolution poses the danger of increasing the divide between the poor and the rich at unprecedented speed.

The digital revolution is already reshaping work, leisure, behavior, education, and governance. Digital technologies 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), education (online learning), public administration (e-governance, e-voting) and the IoT. In general, these contributions of digital technology can raise labor, energy, resource, and carbon productivity, lower production costs, expand access, dematerialize production (from physical books to e-books, for example), improve matching in markets (such as on electronic market places), enable the use of big data (disease epidemiology and drug design), and make public services more readily available (online voter registration, licenses and permits).

Yet 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. Processes of automation have been underway for decades, and one important consequence, it appears, is the net reduction of demand for lower-skilled workers. With 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 working conditions. The fears about rising inequalities have given rise to a new 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. Digital information can be stolen especially with the diffusion of 3D printing where complete information about manufacturing is stored digitally. At the same time, this information can be used to circumvent export and import barriers by simply manufacturing locally with 3D printing. Governments and private businesses can invade privacy and monitor individuals against their will or without their knowledge and in extreme cases destroy real identities. 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 can interrupt or degrade private and public service delivery. Cyberwarfare can paralyze a society by disrupting the flows of information, or destroy machinery connected to the Internet. Social media can be manipulated, undermining democratic processes. The personal use of online technologies can be addictive and cause the onset of depressive disorders. AI codes can incorporate statistical discrimination that may be hard to identify. Instructions for 3d printing in the additive manufacturing can be stolen and applied elsewhere to produce identical parts and products. Special danger relates to advanced weapons. 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'.

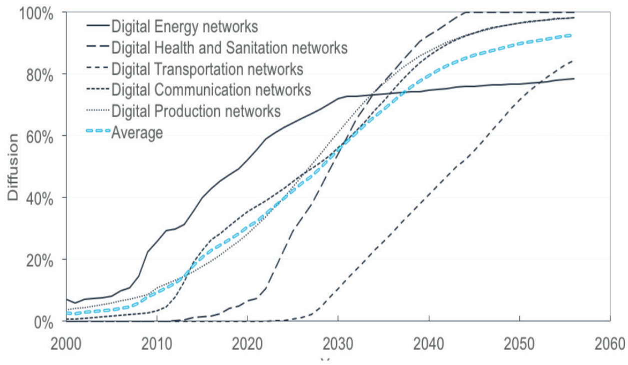

Figure 13. Future diffusion of exemplary and enabling digital infrastructures and technologies. By 2030 most of them, including the average of all, would reach above the 50% mark, or the inflection point meaning that the increase till then would be exponential. This illustrates the possibility of a very vigorous growth of digitalization in the world along with the emergence of new activities and behaviors. The opportunities and potential dangers are high and related to all SDGs. Source: Saniee et al. (2017).

The digital revolution will have even deeper impacts on our societies, creating a next generation of sustainability challenges. General purpose AI 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, in parliaments, in health care organizations, in security organizations such as police and army), complementing, substituting, 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 also start to transform themselves, enhancing cognitive and brain capacities, thinking about how to program brains, how to enhance human capacities. 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.

The digital transformation calls for a comprehensive set of regulatory standards 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 science, technology and innovation roadmaps to better understand the potential benefits and dangers of digitalization. The principles of digital transformation for sustainable development have yet to be written, but some of the likely priorities and example measures are shown in Table 1.

Points of resistance to sustainable development

Success in the transformations to sustainable development also requires a thorough understanding of the potential pitfalls and sources of resistance to change. We identify five major types of resistance, summarized in Table 2.

The first is vested interests, specifically enterprises and individuals who are benefiting in the short-term from unsustainable practices. Two major groups are predominant and include i) the current owners of fossil fuels, who stand to suffer large capital losses from the move to zero-carbon energy, and ii) the beneficiaries of unsustainable land and ocean practices, such as cattle ranchers engaged in deforestation and land clearing and fishing fleets engaged in overfishing.

The second comes from elite groups more generally. Major wealth owners are typically resistant to the taxation needed to fund public services and public investments. Their political influence and threats to move residencies in the face of increased taxation are often enough to prevent political support for necessary public investments. Similarly, major wealth owners of industries engaged in extractive activities (mining, hydrocarbons, fishing, and forestry) are typically resistant to environmental regulation as mentioned above.

The third is the limited capacity of governments to plan and implement policies with time scales of decades, such as the transformation to zero-carbon energy. There are two kinds of obstacles. The first is the political business cycle, and the search for policies with short-term payoffs. The second is technical capacity. Most governments currently lack strong planning units with the capacity to chart technically sound transformation pathways. These capacities need to be built, including through enhanced partnerships of governments, universities, and think tanks.

The fourth is the difficulty of a suitable balance in public-private partnerships. There are two sources of failure. When the private sector is the dominant partner (often because of corporate lobbying), then regulatory agencies can be captured by vested interests. When the public sector is the dominant partner, on the other hand, private initiative and entrepreneurship may be quashed.

A fifth obstacle is a lack of public understanding and a resistance to change. When the public is ill-informed about the challenges of sustainable development and the needed transformations, fear and uncertainty may provoke a 'status-quo bias', and an overall public resistance to change. This is also the case when the government fails to utilize redistributive policies to ensure that winners appropriately compensate losers (for example, displaced workers) during the transformation. Ill-informed publics are vulnerable to populistic appeals to short-run gimmicks and false solutions. And the public will often resist the introduction of new technologies that are feared and poorly understood.

Table 1. Principles for digital transformation.

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

Table 2. Obstacles or the Transformation to Sustainable Development.

Vested Interests	• Owners of Fossil Fuels • Beneficiaries of unsustainable land and ocean practices
Power of Elites	• Resistance of Income Redistribution and Taxation • Resistance to Regulation
Lack of Planning	• Short-run Political Cycles • Shortfalls in Government Planning Capacities
Imbalances in Public-Private Relations	• Regulatory Capture by Private Interests • Stifling of Entrepreneurship by Public Administration
Lack of Public Awareness and Understanding	• Fear of Change • Vulnerability to Populism • Resistance to New Technologies

Finally, the needed transformations are of course highly complex and require long-term change to avoid path dependency. Governments and business often focus on incremental change and lack the tools, institutions, and knowledge to undertake the long-term transformations. As described above, managing such deep and long-term changes will require new policy instruments as well as integrated roadmaps on the way forward rooted in the pathways to sustainable futures. Importantly such roadmaps need to be developed at all levels including regional, national, subnational and cities as these are there levels at which much of the implementation of sustainable solutions will need to occur.

Policy instruments and societal innovations to support the six transformations

The general strategy of sustainable development is to build alliances for change, overcome vested interests, invest in new governance capacities and adopt a range of economic policy instruments to steer the economy and society along the six major transformations towards sustainable development. The guiding principle is that of the economist Jan Tinbergen: there should be as many independent instruments as there are targets or goals. The Tinbergen framework of instruments and targets must of course recognize the time dimension as well. The goal is to steer each national economy, and the global economy as a whole, through the many targets set for the years 2030 and 2050. This process is necessarily complex, requiring national plans that are mutually harmonized to achieve shared global objectives as well.

There is a tendency in public discussions to over-simplify the enormous and complex governance and policy challenges posed by sustainable development. Public discussions tend to focus excessively on short-term policy instruments (such as the macroeconomic tools of monetary and fiscal policy) and on single instruments (or 'magic bullets') to achieve complex and multidimensional objectives. For example, economists have tended to emphasize a 'price on carbon' as the key solution to the challenge of energy transformation, even though the transformation will require several policy instruments, including carbon prices but also regulations on energy and land use, public procurements, energy efficiency standards, directed R&D, and other measures.

There is also a tendency to over-emphasize economic instruments (such as tax and spending policies) to the neglect of other dimensions of policymaking, notably the importance of political and social innovations. The SDGs require collective action, and so it is not surprising that political and social institutions, pioneering actor constellations, and discourses and dialogs on changing norms and values must play a large role in the transformations alongside economic policies. Political institutions are the key conduits for providing public goods; social institutions such as religious institutions and civil society organizations are the key propagators of social norms and cultural values; knowledge organizations of many kinds and cultural actors are incubators of creativity, innovation, and imagination, and therefore key drivers of sustainability transformations. A summary of economic, political, and social institutions, innovations, and instruments is shown in Table 3.

Economic instruments

To promote the needed changes in resource allocation, several types of economic instruments will have to be deployed as a policy package.

The fiscal framework is certainly the single most important set of economic instruments to achieve the SDGs. Many of the transformations involve public investments, for example in infrastructure (SDGs 6, 7, 9, and 11) and R&D (SDG 9). Others involve public financing of services, for example in healthcare (SDG 3) and education (SDG 4). Still others require income transfers to vulnerable groups, such as the alleviation of poverty (SDG 1) and the reduction of inequalities (SDG 10). In all these cases, the respective transformations will require increased budgetary outlays, which in turn will require an adequate level of current and future tax revenues.

Corrective pricing is a second powerful and pervasive tool. When private costs and social costs diverge, as in the case of CO_2 emissions, a corrective price (in the case of CO_2, a carbon tax or a tradable CO_2 emissions permit) can bring private incentives in line with social objectives. Such corrective pricing, most typically through taxes, charges, and tradable permits, is pervasive, and can apply to a wide range of externalities, such as greenhouse gas emissions, the overuse or underuse of ecosystem services, and socially undesirable products subject to abuse with external costs (such as cigarettes and alcohol).

Direct regulation and mandates are a third powerful instrument of government, used far more frequently than most economists recognize. Zoning, protected reserves, bans on hazardous products, building codes, technology standards, safety requirements, labor codes, emissions limits (on vehicles or production processes), energy efficiency requirements, and the like, are all examples of regulations useful for promoting the sustainable development transformations. A recent case of environmental regulation is the move by several countries to restrict or ban the sale of non-electric light-duty vehicles after a certain date in the near future.

Development financing is a fourth major area of policy. Development financing is a form of project financing in which an official funding agency (such as a multilateral or national development bank) works with government entities to plan and execute a complex investment project. The project typically requires a set of policy measures (budget, regulation, pricing) and policy processes (such as public consultations, environmental audits, legislative actions, and community participation) alongside the mobilization of financial instruments. The funding may involve private sector funding (bonds, bank loans, venture capital, etc.) alongside public funding, and the implementation of the project may involve both private companies and public agencies. The major characteristic of development financing is complexity: the need to combine funding, public oversight, and policy measures with the investment outlays.

In addition to budgets, corrective prices, direct regulation, and development financing, governments possess a set of further policy instruments. These include: public procurement, publicly directed R&D, information disclosure requirements (for example on patents and financial instruments), company law, liability law, bankruptcy code, licensing, technical standards (e.g., for 5G wireless broadband), public auctions (e.g., of electromagnetic spectrum), and public land management practices.

Table 3. The sustainable development policy instruments.

Economic Instruments	• Fiscal Outlays: - Public Services - Public Investments - Transfer Payments and Redistribution • Fiscal Revenues and Public Debt: - Taxation - Tolls and Tariffs on Public Services - Deficit Financing and Debt Management • Corrective Pricing • Direct Regulation (Land, Labor, Technology) • Development Financing • Public Procurement • Publicly Directed R&D • Legal Standards: Disclosure, Company Law, Liability Law, Bankruptcy Code, Licensing • Technical Standards • Public Land Management • Auctions of Public Assets (e.g., EM Spectrum)
Political Instruments	• Integrated Planning • Public Deliberation • Public-Private Partnerships • Independent Commissions and Agencies • International Diplomacy • Democratic Oversight of Science and Technology • Official Sustainable Development Metrics
Social Instruments	• Public Awareness • Social Norms and cultural innovations • Grassroots Activism • Investment activism • Consumer activism • Shareholder activism • Moral Teachings of Major Religions

Public institutions, political instruments, and transformative governance

We identify several public institutions and political processes needed to support the six transformations to sustainable development. The single most important of these is government-led integrated planning. Every government needs a way to plan for the SDGs taking into account the complex synergies and tradeoffs across the various SDGs. Typically, this work is undertaken by the planning agency (such as the Indonesian National Planning Agency BAPPENAS and the Chinese National Development and Reform Commission), the economy ministry, or an inter-agency task force chaired by a senior cabinet official such as the prime minister or deputy prime minister.

A second major institution is public deliberation. Governments often produce preliminary papers (sometimes called 'green papers') to elicit public feedback. Commissions are established together with national science academies. Universities are recruited to provide research overviews. Public 'town hall' meetings are undertaken around the country by public officials to obtain first-hand feedback. Surveys may be undertaken to elicit public opinion.

A third major public institution are public-private partnerships, in which a formal partnership is formed between government agencies (often serving as funders) and private business (often serving as implementers). Public-private partnerships are pervasive in sustainable development, typically because the private sector is the exclusive holder of the requisite technologies and large-scale management capacities, with the public sector needed to mobilize resources for public goods that would otherwise be underprovided by the market.

A fourth major public institution are independent agencies established to implement long-term policy frameworks. When policy challenges are complex, politically charged, and with a time horizon beyond that of the election cycle, it is often expedient to establish an independent agency or commission to oversee the long-term policy implementation. Decarbonization policy is a case in point. The decisions on the siting of long-distance transmission lines and renewable energy sites (e.g., for wind, solar, and hydro power) are often fraught with lobbying pressures. Decision making might then usefully be removed from the fray of day-to-day politics. Just as modern central banks were given their policy independence, subject to democratic oversight but not direct political intervention, a decarbonization agency might be tasked with establishing timelines, protocols, bidding, and funding streams to bring about long-term systems change, subject to general democratic scrutiny by elected officials.

The fifth political process is the tools of international diplomacy and law to secure the benefits of cross-border cooperation. Most of the environmental SDGs require significant international cooperation. Biodiversity, climate change, freshwater and ocean conservation all require cooperation at a trans-national scale, often at the scale of a watershed or ecosystem. Global treaties, technical working groups, regional and international development banks, and UN agencies are various institutions established to secure the needed but fragile cross-boundary cooperation.

A sixth political institution is the democratic oversight of science and technology. The oversight of science is crucial not only to prevent scientific mishaps and abuses, but to ensure the public's confidence in scientific conclusions. When that confidence is lost, the costs can be very high. The anti-scientific campaigns against vaccination, for example, are leaving large numbers of children needlessly exposed to diseases because parents lack the confidence to immunize their children in the face of unsubstantiated claims that vaccinations pose substantial health risks. To maintain public confidence in AI, genomics, biodiversity conservation, energy transformation, healthy diets, and so on, there will have to be a high public confidence in, and understanding of, expert opinions. Special consultative and oversight bodies can be crucial in explaining science to the public and feeding public doubts back to the scientific and engineering communities.

Finally, we should note the critical role of official SDG data that is produced by credible public agencies to track progress or lack thereof in achieving the SDGs. Governments undertake censuses, publish budgets, produce surveys, and publish official data. All of this is invaluable in creating systems of public accountability so that governments are kept to their word. Of course the data must win the public's confidence; and cases of political meddling in official data can leave long-term scars and mistrust that can deeply undermine governance and block economic progress. Every government should maintain and publish a credible and high-quality set of SDG indicators to track SDG progress, support policy management, and keep governments accountable to their commitments.

Societal change and social policies

Economic and political innovations and instruments are the tools of government. Yet large-scale societal transformation also depends on social movements, actors of change, societal values and public acceptance. Often, large-scale social change is won first in the hearts and minds of the people, and only afterwards accepted in legislation and economic policies. This is the case with the mass movements against slavery, led by William Wilberforce, against colonialism led by Mohandas Gandhi, against apartheid led by Nelson Mandela, for civil rights led by Martin Luther King Jr., and for women's rights led in the UK by Emmeline Pankhurst, reproductive rights, and sexual rights, led by countless activists. In these cases, the battle for transformation started with social movements, actors of change, it was first a battle for hearts and minds, leading later to legislation and international law.

The movement for sustainable development is also a battle for hearts and minds. Humanity must be convinced to care about nature, the planet, the future, the poorest of the poor, and the dignity of people all over the world. And those moral opinions must prevail against the determined opposition of vested interests, such as the large fossil-fuel companies of the United States that are lobbying the US Congress to oppose the global consensus in the Paris Agreement on climate. Public values must change, and social change has its own mechanisms for promoting broad changes in public attitudes and in behavior.

The starting point is public awareness. All social movements inherently depend on a widening arc of public awareness and understanding, often catalyzed by science and science communication. Environmental activists since Rachel Carson in the 1960s, the Club of Rome in the 1970s, and Dr. James Hansen since the 1980s, have been advocating for action to address the risks of human-induced environmental degradation. Similar campaigns have been underway for decades to end poverty and hunger, promote gender equality, and ensure equal access to health, education, and other basic needs. Indeed, one can say that the Universal Declaration of Human Rights (1948) is a moral charter of civil society that already 70 years ago expresses many of the foundational principles of sustainable development, especially regarding social inclusion.

A second step is to establish social norms. In this regard, the Brundtland Commission of 1987 must be seen as a global watershed, by introducing the concept of sustainable development and famously defining it in terms of intergenerational responsibility (meeting the needs of the current generation without compromising the ability of future generations to meet their needs). Agenda 21, adopted at the Rio Earth Summit in 1992, was a second major step, although Agenda 21 has so far failed to achieve sufficient public awareness and political commitment to reverse the course of environmental degradation.

The MDGs, adopted by the UN member states in 2000 to be achieved by 2015, can be seen as another watershed in global public awareness. This effort initiated by then UN Secretary-General Kofi Annan caught the attention and imagination of governments and civil society around the world, and gave an enormous impetus to the fight against extreme poverty. In 2005, civil society, supported by Nelson Mandela, campaigned "to make poverty history," giving an added impetus and sense of urgency to the MDGs. The MDGs were of course followed by the SDGs in 2015, which combined the fight against poverty with the struggles for social inclusion and environmental sustainability. The SDGs therefore offer, for the first time, a clear and understandable set of global goals constituting sustainable development.

A third step in a social movement is grassroots activism. The fossil-fuel divestment movement, calling on asset managers of pension funds, insurance funds, and university and foundation endowments, to divest of holding in fossil-fuel companies is a prime example of mass social action that is both symbolic and substantive. Trillions of US dollars under management have by now committed to invest according to environmental, social, and governance (ESG) objectives, including divestment from various fossil-fuel-based energy companies.

Similar kinds of grassroots activism are witnessed in consumer boycotts and the preferential purchases of goods and services from companies that abide by ESG objectives. Fair Trade coffee is an important example. Consumers pay more for Fair Trade coffee with a portion of the proceeds returned to farmer cooperatives that abide by agreed principles of good governance.

Shareholder activism is yet another example of effective grassroots campaigning. In US company law, shareholders meeting certain minimum ownership criteria are able to launch shareholder resolutions that goes for a vote by all shareholders. Activist shareholders of ExxonMobil, for example, launched a shareholder resolution to require the company to report on how climate change regulations could affect the company's assets and future profitability.

A fourth component of mass social transformation is to expound the moral teachings of the world's major religions in the context of sustainable development. Pope Francis' encyclical *Laudato Si'* (Pope Francis, 2015) has inspired individuals around the world to fight for climate justice and help for the poor. Ecumenical Patriarch Bartholomew of the Eastern Orthodox Church has made remarkable efforts for more than a quarter century for ecological justice. Other major religions are similarly joining the global movement for sustainable development and climate justice.

Transformation towards sustainable future is possible – but ambitious action is needed now!

The world and almost all regions are currently off course from achieving the SDGs. Yet with a bold and appropriate deployment of policy instruments, the world economy can be steered to achieve the SDGs in 2030 and 2050. Based on our overall assessment, we conjecture that the incremental global costs of achieving the necessary transformations will be no more than 4% of global output per year. The key is to raise national saving rates by a few percentage points of national income and invest the incremental saving on priorities such as zero-carbon energy, high-quality schools, improved health systems, environmental conservation and restoration, good governance institutions, and global cooperation initiatives to leverage dynamics towards the implementation of the SDGs. This study shows how the incremental saving should be deployed to bring about six key transformations that will raise living standards, promote jobs, ensure social inclusion, and protect the natural environment, in short, to achieve "the future we want."

1 Framing and Introduction

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1.1 The global agenda for sustainable development

One of the most pressing challenges humanity faces is how to realize the benefits of global social and economic development within a safe and just operating space of a stable Earth system. There is significant inequality between and within societies with billions left behind and overwhelming evidence of rising global risks due to ever-increasing human pressures on the planet. Ensuring future sustainable development for all will require socioeconomic development for improved human well-being while preserving Earth system resilience, referred to as sustainable development within planetary boundaries.

In 2015, the United Nations adopted the 2030 *Agenda for Sustainable Development* including 17 Sustainable Development Goals (SDGs, UN, 2015b) which provide an aspirational narrative and goals for the desired future for human development with an actionable agenda to be achieved by 2030. It specifies far-reaching time-bound, often quantified, objectives based on the most comprehensive consultation held so far among nations. For the first time, a world development agenda is adopted that integrates far-reaching and aspirational goals for inclusive social and economic development, to occur within global environmental targets for oceans, freshwater, biodiversity, and climate, i.e., essentially a roadmap for redefining sustainable development as a people and planet agenda of achieving a prosperous and fair world within planetary boundaries. Together with the 2015 Paris Agreement (UNFCCC, 2015), which commits all signatories to a long-term target of holding global warming to well below 2°C above preindustrial levels, as well as the 2015 Addis Ababa Action Agenda (UN, 2015a), the 2030 Agenda recognizes the necessity of attaining social and economic development within the safe operating space of a stable and resilient Earth system.

The High-level Political Forum (HLPF) on Sustainable Development is the United Nations central platform for the follow-up and review of the 2030 Agenda and the SDGs. The Forum, which meets annually, provides political leadership, guidance and recommendations on the 2030 Agenda's implementation and follow-up; keeps track of progress of the SDGs; spurs coherent policies informed by evidence, science, and country experiences; and addresses new and emerging issues. Since the adoption of the 2030 Agenda, the Forum has chosen to undertake in-depth reviews of progress for a subset of related SDGs each year. In 2018, the theme will be *Transformation towards sustainable and resilient societies* under which Goals 6, 7, 11, 12, and 15 will be reviewed. Progress on Goal 17 – *Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development*, is reviewed each year.

1.2 Why TWI2050 is needed

The urgent question now is how to act on this aspirational agenda. To do so, the global community needs to have a clear understanding of the full consequences and cost of inaction and the benefits of achieving SDGs in every major region of the world. While the SDGs provide normative guidance on the direction of change that should be pursued, the exact pathways depicting how to get there are far from clear. There are several challenges associated with identifying pathways that achieve the SDGs. Firstly, the targets associated with the SDGs have been set mostly without considering all interactions among the goals, however, it is probable that progress towards one SDG will inevitably create trade-offs and synergies in the progress towards achieving SDGs.

Secondly, the SDGs in a way extrapolate the present to the future, i.e., they assume that current preferences and trends do not change substantially and no major unforeseen hurdles or tipping points occur over the next 12 years; whereas in reality, the SDGs will be more a moving target, since the only thing certain is that the future is uncertain, and the deep and radical transformations necessary to achieve the SDGs and their interactions will likely, and necessarily, result in significant, and perhaps unpredictable, changes in human behaviors and social structures along the way. Moreover, transformations towards the SDGs have to cope with global mega trends, such as the digital revolution, that are driven by path-dependent second-order dynamics.

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

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

TWI2030 focuses on six transformations that capture much of the global, regional, and local dynamics and encompass major drivers of future changes: i) Human capacity and demography; ii) Consumption and production; iii) Decarbonization and energy; iv) Food, biosphere and water; v) Smart cities; and vi) Digital revolution. Together they give 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.

1.3 TWI2050 framework

A starting point to analyze pathways towards goals is to establish an agreed framework. TWI2050 proposes an overarching framing narrative and quantitative and time-bound targets and indicators that set the outer boundary conditions for the transformation of the world between now and 2050 through the SDGs and the Paris Agreement. The objective is to thereby mobilize the international research community to explore multiple sustainable development pathways (SDPs) by applying backcasting analyses of how to achieve the goals in the framing narrative at multiple scales. At an overarching level the objective is to achieve all SDGs by 2030, and by 2050 continue meeting all SDGs in an evolving prosperous and just world for all while stabilizing the Earth system within planetary boundaries and remaining cognizant of Earth and human systems dynamics on longer time horizons out to 2100.

The TWI2050 framework (Figure 1) includes qualitative and quantitative elements and consists of the following: i) a broad transformational narrative, ii) targets and indicators for the 2030 and 2050 and iii) specific sustainable development pathways (SDPs) that include quantitative elements based on modeling approaches. These are paired with governance elements that induce the transformations and are thus an integral part of the overall framework. There can be many alternative pathways that explore branching points, lock-ins, resilience, inclusiveness, cooperation and differing transformational dynamics. The TWI2050 framework is designed to allow modeling and analytical groups to identify and explore a portfolio of measures needed to achieve all SDGs jointly accounting for synergies and trade-off. With such common goals, and agreed common assumptions, the framework facilitates inter-comparison of results. This report presents a number of exemplary sustainable pathways derived from recent analyses such as the Shared Socioeconomic Pathways (SSPs, Riahi et al., 2017).[1] These pathways provide the basis for the fully integrated SDPs that will be developed in the next phase of the initiative.

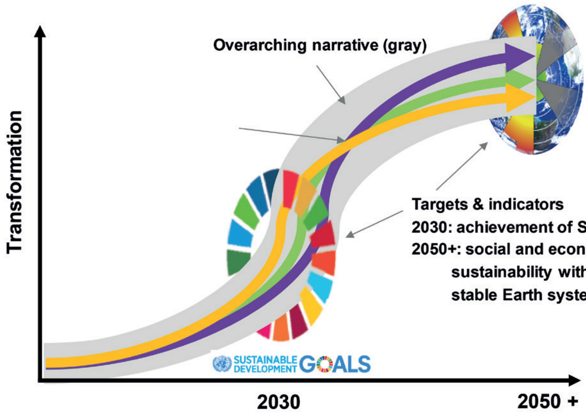

Figure 1. An illustration of TWI2050 conceptual framework. Two sets of science-based, normative targets provide bounds for the transformation toward sustainable future. The first are symbolized by the SDGs for 2030 and the second for 2050 and beyond symbolizes the achievement just and equitable future for all on a resilient planet. The gray band illustrates the overarching narrative that indicates how the future is connected to the present. It is about what needs to change to achieve the transformation toward sustainability by 'backcasting' from the normative targets. Also shown are alternative sustainable development pathways (SDPs) that provide model-based quantifications of the transformational changes. They can be interpreted as alternative realizations of the overarching narrative. SDPs in this report are indicative and the next phase of TWI2050 will focus on more integrated pathways although some characteristics would remain to be qualitative such as justice and peace. Source: TWI2050.

1.3.1 Overarching sustainable development narrative

At the center of the framework is the overarching and 'framing narrative'. This provides largely qualitative boundary conditions to be met within which SDPs can be explored. Here are some of the key elements of the narrative:

Globally and rapidly, awareness grows that the universally adopted SDGs can only be achieved through an unprecedented transformation of the global economy and societies worldwide. Only through such a transformation, is it possible to achieve a world in 2050 that is characterized by prosperous, equitable, and inclusive societies safely operating within planetary boundaries.

[1] The SSPs are based on five different development routes for societal trends: i.e., sustainable development (SSP1), global fragmentation (SSP3), strong inequality (SSP4), rapid economic growth based on a fossil-fuel intensive energy system (SSP5) and middle of the road developments (SSP2). Each of the SSPs has been elaborated in terms of a storyline and various quantifications using models. The sustainable development scenario (SSP1) combined with stringent climate policy can also be seen as an example of a scenario exploring the route towards a more sustainable world – but it should be noted that the SDGs were not targeted in its development.

Support for such transformational change emerges from rising societal uneasiness of slow progress on environmental and societal concerns, and linked to renewed impetus to meet international agreements. This plays a role at the very local scale, where seeds for transformative processes continue to grow - but also in key sectors such as finance.

As a result, driven by a growing awareness of the social, cultural, and economic costs of unilateral decision making at all levels, a new joint global cognitive and normative framework emerges that provides the necessary perspective to tackle the world's sustainability challenges. Heterogeneity of values and norms among societal groups, including religions and nations continue, but are generally better aligned with this new 'global identity' based on shared responsibilities and vision for a sustainable future. Inequality is greatly reduced within and between countries. The number of conflicts falls rapidly, and the world enjoys extended periods of geopolitical and social stability.

This overall change in mindsets, coupled with more effective governance for long-term sustainability, facilitates six interconnected transformations:

Human capacity and demography. In low-income countries premature causes of death decline rapidly through the provision of universal preventive and curative medical care. Improvements in health care in the developing world lead to increased life expectancies which by mid-century are comparable to those in the developed world. Investment in education increases dramatically with a special focus on girls in the developing world such that by 2030 enrolment levels are achieved that lead to universal attainment of primary and secondary education levels for both boys and girls. This contributes to a demographic transition towards slower global population in the order of nine billion by 2050 and decreasing to current levels by the end of the century. Slower population growth has led to a gradual ageing. New employment demand arises in the health, education, research, and social sectors. Digital revolution places high demand on high educational attainments and skills.

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

Decarbonization and energy. By 2050 the world has largely decarbonized and is accompanied by universal access to clean, affordable modern energy services. The seeds of this transition can already be seen in the rapid technology development in key sectors, such as renewable energy, electric mobility, and battery storage. By 2030, global greenhouse gas (GHG) emissions have been falling for some time as all nations start to follow deep decarbonization pathways towards net-zero GHG emissions. Focus is on the provision of energy services, whereby energy supply is a combination of both centralized and decentralized systems, with high energy efficiency standards being the norm everywhere. Together with behavior change and technological innovation this leads to reduced energy demand and large savings on the energy supply side. Moreover, there are reinforcing feedback loops enabled by government incentives and other dynamics, for example huge investment in sustainable resilient and efficient infrastructure, technological breakthroughs and cost decreases, sector coupling and digitalization, and behavioral change and energy self-sufficiency..

Food, biosphere and water. The 2050 vision requires the sustainable use of land that both provides sufficient food for all and supports global biodiversity. By 2030, global agricultural productivity is significantly increased through sustainable intensification of the agricultural sector with the adoption of agro-ecologic elements and better functioning of agriculture markets. The agricultural demands for freshwater are reduced and the expansion of agricultural land has halted to preserve remaining biodiversity and enhance the resilience of carbon sinks. Improved management of artificial fertilizers greatly reduces nutrient pollution of marine and freshwater ecosystems. Hunger and malnutrition are eliminated with universal access to clean, safe, nutritious food year-round. Worldwide, diets are significantly healthier, implying reduced reliance on meat. This means that food production can be less resource intensive than today, while food waste and food loss can be significantly reduced through more localized distribution. Fish stocks and other marine resources are sustainably managed, and levels of marine pollution significantly reduced improving the health of marine ecosystems. These changes together allow biodiversity loss to halt. Food systems and other anthropogenic land and marine use serves to store carbon and enhance biodiversity.

Smart cities. By 2050, the world's cities remain innovation engines and have transformed to prosperous, thriving, livable metropolises with low levels of pollution and high resilience. By midcentury, cities are carbon neutral. Digital progress has changed the nature of urbanization with more people able to connect to the dynamism offered by cities in more remote locations, leading to increased integration of the urban hinterland. Former informal settlements and slums are now livable settlements. Urban transformation pathways differed significantly between developed and developing nations and local governments acted as primary agents of change. Global and regional hubs are more connected. Despite this increased interconnectivity settlements are more self-sufficient, less polluting, and circular in terms of resource consumption. Housing is no longer considered a purely private shelter and is an essential component of a larger social system giving people better opportunities to connect with each other. Transport solutions are more integrated and systemic, autonomous, emissions free, and increasingly shared. Longer-distance travel is undertaken largely by a combination of fast rail, magnetic levitation transports and low- or zero-emission aircraft.

Digital revolution. The 'Fourth Industrial Revolution' is the key driver of the sustainability transformation. Digital technologies support the transition to zero-carbon societies, circular and resilient societies. By 2050, the convergence of transformative digital technologies have far-reaching consequences across all sectors and for the organization of societal life though innovations for example in artificial intelligence, block chain, big data, additive manufacturing, robotics and synthetic biology. Effective mechanisms are established that steer the transformation towards the benefit of humanity instead of eroding human control or intruding on human rights of privacy and freedom of access to information. Completely new professions arise, and novel resources become available for roles that cannot be substituted. The sharing economy emerges as a significant component of economic activity and employment. Advances in synthetic biology have resulted in significantly increased agricultural yields, healthier foods, and improved and more personalized health care. Technological progress remains a key driver and enabler of sustainability outcomes, supported by major investments in research and development and generating new employment opportunities.

Spurred by these transformations developing countries grow rapidly and there is a gradual, conditional convergence between developing and developed countries, resulting in overall reduced income inequalities. Globally economic activity moves away from a focus on growth per se to be more broadly based on individual and social wellbeing and towards achieving global and national development and sustainability goals.

To support these transitions, global governance becomes more effective throughout the period. This requires improved international cooperation and fair-trade rules, and in due course new, international policies are introduced, such as transnational minimum tax standards to avoid competitive, destructive underbidding. In general, there is a shifted emphasis to lower taxes on desirable activities, such as labor, and to higher tax on undesirable and destabilizing developments such as pollutants and unsustainable resource use. There is a system of global carbon pricing in place and risky financial market transactions prevented via a Tobin tax. Further reductions in wealth inequality are achieved through a variety of means and incentives.

The advances in human capacity and empowerment strengthen multilateral institutions and transnational networks. This has led to a growing awareness and acceptance of solutions to meet the challenges of increasing global resource constraints, economic and environmental crises, and societal stability that cannot be addressed by market forces or private decision making alone.

Stabilization of the Earth system through aligned investments in local, national, and global commons has become the new imperative in the world. Socially responsible institutions are entrusted with the provision of the corresponding goods and services reflected in a new 'social contract' rooted in the SDGs and based on shared responsibility and vision for a sustainable future. The social contract is also reflected in new governance structures, where global regimes, transnational networks, and standards are developed further, pushed, and implemented by multi-actor constellations. Transformations are spurred by pioneering actors. Sustainability oriented investments and deep reforms in regional and multilateral organizations facilitate the transformation towards a human-centered paradigm shift in the global economy. There is a transformation from a basically inter-governmentally driven international system to an emerging pluralistic and diverse 'global society' characterized by an exponential growth of transnational networks, transnational cooperation alliances and actor constellations, giving birth to a polycentric, poly-lateral global order.

Changes in resource transformation processes have reduced the human impact on Earth and ecosystems to a minimum. In 2050, the global economy is operating within the planetary boundaries that regulate Earth system stability. The rate of change of the Earth system due to anthropogenic interference is slowing. By 2100, Earth system processes have enabled the world to continue evolving within a manageable inter-glacial state. The long-term rate of change of the Earth system due to anthropogenic causes approaches zero. Nevertheless, in reaching this new state the Earth is significantly transformed compared with the present with changed patterns of human, plant and animal distribution resulting from the irreversible impacts of climate and other Earth-systems changes.

TWI2050 is based on one broad, overarching narrative that includes some variants, with the possibility for sub-narratives for individual pathways and regional and national perspectives. For example, this could include the narratives in Africa, Asia, North and South America, Asia and Europe that might be combined to form a coherent and more comprehensive global narrative.

1.3.2 Targets and indicators

TWI2050 identifies two multidimensional, science-based targets, one for 2030 and the other for 2050 and beyond in terms of quantitative and qualitative characteristics consisting of boundary conditions applying to every major region of the world. In the 2030 Agenda, nations agreed on 169 targets to be reached by 2030. However, the full set of SDG targets (and related indicators) cannot be directly used in a scientific assessment. First, some targets cannot be operationalized in quantitative scenario analysis. Second, a more concise set of targets is needed to focus model analysis and comparison of results across models and to facilitate better communication to policymakers. In the end, a wide array of analytical approaches, and different sets of indicators (tier-based system) at varying degrees of granularity is needed. While the 2030 targets can be informed strongly by the SDGs, the 2050 values would need to maintain this ambition level or further progress and ensure developments stay within planetary boundaries. This may include additional indicators and adaptations as science advances. Accounting for dynamics post 2030 warrants a longer-term view and greater flexibility in sustainability implementation.

TWI2050 is using experts and stakeholders from relevant fields to undertake a selection process for determining targets and indicators based on a consistent set of selection criteria. This process allows TWI2050 to reduce the full set of targets and indicators for the SDGs to a list of 'essential targets' for each SDG. Reducing complexity while limiting information loss helps both modelers as well as communication with policy makers. The main objective is to specify targets as quantitative information to complement the TWI2050 overarching narrative.

Following this process, TWI2050 will identify two multidimensional target spaces, one for 2030 and the other for 2050 and beyond, in terms of quantitative and qualitative characteristics consisting of boundary conditions applying to every major region of the world. Each target space will comprise a set of targets and indicators, corresponding to each SDG.

It is important to note that the target space is not intended to be an alternative set targets or indicators for achieving the SDGs. Both sets are important, but based on very different selection criteria, and serve very different purposes. The SDG targets provide the 2030 Agenda the necessary specificity and aspiration of what needs to be done to achieve the individual goals, whereas the target set to be proposed by TWI2050 aims to support quantitative analysis and to serve the scientific community by providing a standardized set of boundary conditions which can be tested and evaluated in multiple scenario studies.

1.3.3 Sustainable development pathways

The Sustainable Development Pathways (SDPs) represent the myriad routes from the present to 2050 and beyond, across domains and sectors, for example, energy, urbanization, technology, governance, education, and food security (Chapter 3). The objective is for the framing narrative to function as a common set of generic boundary conditions to allow modeling groups to develop and analyze multiple SDPs that explore transformations within this narrative and associated target spaces. The SDPs will consist of quantifications and qualitative storylines which support operationalization of multiple pathways to meet the target spaces.

The pathways may differ along branching points describing different development characteristics, such as technological vs. behavior change in the energy system; or dynamics of transnational governance vs. unilateral political power politics in the global political system. The pathways encompass at relevant scales, for example, population, technological, economic, and environmental dynamics. They include, for example, the quality of institutions and governance, shifting values and norms, the levels of corruption or equity. The assessment of possible branching points and differing characteristics across the pathways can be a tool for determining important trade-offs among the achievement of SDGs and human development within planetary boundaries. The TWI2050 framework will facilitate analysis of essential conditions and options for flexibility within the SDPs in line with the overarching narrative.

1.4 Outline of the TWI2050 report

This report comprises key messages, synthesis and four chapters. Chapter 1 introduces TWI2050 framework. The narrative and target spaces are presented briefly here in Chapter 1 and will be further refined in the next phase of TWI2050 and published.

Chapter 2 examines, at the global scale, some major current trends in demography, economics, finance, society and politics. It presents potential major tipping points and dynamics that are likely to interact thereby creating a very different world from the present. It assesses currently observable megatrends and historical patterns with corresponding path dependencies. The chapter points to several of these megatrends that need to be taken into consideration how to achieve the transformation to sustainability.

Chapter 3 investigates the characteristics of pathways that would lead to a sustainable future. It first assess the scientific literature on pathways that achieve several SDGs. Next, implications of the linkages across SDGs are highlighted by presenting model-based pathways which follow an integrated approach with special emphasis on the six transformations. Pathways are presented that feature SDGs under review at HLPF 2018 (SDGs 6, 7, 11, 12 and 15). The chapter concludes with a discussion of research implications.

Chapter 4 presents - from multiple perspectives - the governance framework required to achieve and steer transformations toward sustainability. This governance framework comprises of both fine tailored policy principles across the social, economic and political domains as well as enabling conditions for the great (societal) transformation that is needed to achieve the sustainability aspirations.

The main findings and conclusions of the four chapters are summarized in the Synthesis presented at the beginning of the report that also connects them to policy interventions.

2 The Challenge Ahead: Non-linear Interactions in Current Societal Dynamics

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Key Messages

1. Sustainability is a societal issue

For many years sustainability issues were principally the domain of the natural and life sciences. Now they are studied as socioenvironmental system dynamics in order to mitigate the consequences of human behavior, rather than studying how to change that behavior itself. We must finally acknowledge that *the real sustainability challenge is societal, not environmental.*

Societies define and shape what they consider their environments, what they see as the main challenges in those environments, and what kind of solutions they can try and offer. Hence, *placing society at the center of the sustainability debate* is the next quantum jump to develop in our thinking.

Over long-term time, the many human societies on Earth have developed different ways to interact with their environments, through a co-evolution between perceptions, ideas, values, institutions and ways. We must investigate these at the global level as well as at that of the cultures involved.

2. The importance of the long term

Most current sustainability research is confined to the study of the last couple of centuries. This is insufficient because in doing so we cannot understand three different aspects of the complex processes involved:

- The slow, millennial, societal and natural dynamics against which the faster, shorter-term dynamics play out – tectonics and deep cultural evolutions for example. These are not easily noticeable at shorter timescales, but can play important roles;
- The full range of system states that socioenvironmental dynamics can assume – there may have been such states in the past that could be useful to understand in the present. Biological agriculture, for example, harks back to farming before the invention of chemical fertilizers and pesticides;
- Second order changes (changes in the way change proceeds) that reveal important dynamics that often play out very slowly, at deep levels, and change the dynamics driving shorter-term processes.

Moreover, such a short-term approach looks at the current, highly disturbed state of the socioenvironmental system without understanding other, less disturbed ones. It is as if one would be trying to heal a very ill patient without knowing what a healthy person looked like.

3. The sectorial approach is not getting us any further.

By studying the dynamics of individual sectors of our terrestrial life-support systems (water, biodiversity, food security, climate, energy etc.) we cannot take the many connections between these subsystems (and others) fully into account, thus missing crucial interactions. Well-nigh thirty years of research have enabled us to know the sectorial dynamics of such domains rather well, but have not brought us much closer to understanding the ways in which they are connected. *We need to adopt a holistic approach to reach the next level of understanding of the very complex socioenvironmental dynamics that have driven us into the current sustainability conundrum.* This goes against a long-standing tradition of western thinking that isolates parts of a whole, studies them in detail and then assumes that by bringing them together we gain a perspective on that whole. Thus we distinguish between nature and society, as well between scholarly disciplines. Those distinctions shape many of our practical decisions about the environment, as well as our research.

In practice, however, the whole is more than the sum of its parts. T*o truly understand the dynamics involved holistically, we must achieve intellectual fusion between disciplinary ways of thinking*, and that is hampered by our education as well as our career- and science funding structures.

4. To think about our future, we need to use a Complex Adaptive Systems approach

Rather than be reactive to the dynamics driving us towards unsustainability, we have to become pro-active and begin to *design for change*. That implies *learning from the past about the present* (as we currently do) ***for the future*** (which we don't usually do). Our western science originally developed to explain the present by systematically proving its theories and ideas, which one cannot do for the future. Thinking about the future was therefore not conducive to one's scientific career.

The Complex Adaptive Systems approach responds to this need in that it assumes that all systems are complex, that "Occam's razor" (always opting for the simplest theory) is not helpful, and that *instead of focusing (ex post) on the origins of dynamics*, we *must (ex ante) study the emergence of novelty, acknowledging the fact that multiple futures can emerge at any point in a system's trajectory*.

5. The ICT revolution is accelerating many ongoing trends

Currenty, the acceleration of the Information and Communication Technologies (ICT) is rapidly accelerating a number of societal trends that have begun long before this latest technological revolution. Among these are:

- The desintegration of the rules that govern the interaction between (nation-) states;
- The underming of the structure of our representative democracatic systems;
- The destruction of communities based on solidarity, particularly in urban contexts;
- The loss of control over information processing that led to a relative convergence of societies around basic norms and values;
- The reduction of the dimensionality of our experience through television, film and computer gaming.

Together, these trends are affecting the very basis of our current social structures and insitutions. They will produce major societal tipping points once they start interacting more closely, and this might very probably happen before 2030 or 2050, thus putting in jeopardy our chances of achieving the SDGs.

6. Exceeding planetary boundaries is destabilizing our environment

All this must be seen in light of the environmental tipping points that will result from current developments in climate, biodiversity, pollution of land and sea, saturation of the environment by certain chamicals, etc. The interaction between these ongoing natural processes may well cause major environmental tipping points alongside the societal ones mentioned under point 5, either before or after 2050. Such a conjunction of societal and environmental tipping points on a global scale is unheard of in human history, and may well lead to a period of chaotic system behavior, in which the current symbiosis between humans and their natural environments is profoundly distorted, societies will lose their current structure and people will be at a loss on how to proceed. The threat of societal instability makes the search for staying within environmental boundaries only more urgent and important.

7. From here to the future and back, or the inverse?

To project into the future is, of course, fraught with difficulties. It can be done in two ways. Either one extrapolates from the present to the future, or one determines what kind of future is plausible and desirable and then constructs a roadmap from the present to the desired future. In the former case, the resultant futures are constrained by present-day thinking and existing trends, while the second approach does enable us to conceive "out-of-the-box" futures, but it is more difficult to see how these could be realized.

We must link these two ways of conceiving our future. On the one hand, we should project a fundamentally different (sustainable) future, to be implemented differentially across countries, while on the other we must assume some form of "progress" from the present to that future or futures. This dilemma requires that one 'sails between Scylla and Charybdis', following a very narrow set of paths. The methodology for such a way forward is in many ways still to be developed, so that we can take the possibility of fundamental changes in our socioeconomic and environmental conditions into account. Our models are an attempt at moving forward in that domain.

8. We need to know much more about human perception, cognition and decision-making

These topics have thus far remained outside the core of the sustainability sciences, yet they are essential in understanding and where possible predicting how the system (or parts of it) might behave. There are a number of major potential choices coming up if we are to attain a sustainable environment, such as "What role to accord to future technologies?", "How to improve the global governance system to avoid major tipping points?", etc. But there are also, in daily life, myriad decsions that cumulatively impact on the overall trajectory of our Earth system. So in both (and other) instances it is of great importance to understand biological or societal dynamics that might impact on decisions taken.

Any and all of these decision also have unintended consequences, and improving our capacity to look for these and evaluate decisions against the options that we open at the time but were not chosen, is another domain that, if better understood, could contribute to improving our chances for a sustainable long-term socioenvironmental system.

Many of our societies are now at a tipping point where they can step up the pace of transition towards implementing the 2030 Agenda and the Paris Agreement. This tipping point situation is characterized by three major bifurcations: The transformation towards sustainability, nationalist counter-transformations and the far-reaching dynamics of the digital transformation.

2.1 Introduction

One of the assumptions of the Sustainable Development Goals (SDGs) is that achieving the vision underpinning the SDGs will be possible on the foundations of our current global socioeconomic system and its natural environment. This chapter places some question marks behind that assumption. The first of these concerns the future of the global socioeconomic system and the environment in which it functions. There are many signs that we are currently involved, worldwide, in a major transformation of the global societal world order: the shifting of the political structure from the long-standing Euro-American to an East-Asian center of gravity; the rapidly emerging self-confidence of Islam as a global force; the emergence of Africa as a developing continent, etc.

Other issues also provide warning signs of potentially complicating developments, such as the ever-increasing wealth discrepancy in many countries that might trigger social tensions; growing insecurity around the provision of basic environmental services such as food and water, which may lead to (inter-) national conflicts; emerging identity-related populist tendencies that are in contrast with the wave of globalization that we have seen over the last half century.

Moreover, the current Information and Communication Technology (ICT) revolution has, and will continue to have, a major (and accelerating) impact on these issues by fuzzing the distinction between signal and noise, undermining our societies' alignment around certain existing worldviews and values, as well as transforming human communication.

In this chapter, we will (in Section 2.2) signal, in the form of narratives, some of the tendencies that might emerge. We acknowledge that looking into the future is fraught with difficulties and uncertainties, but it clearly is relevant to include these emerging trends in any considerations relative to the future of our planet and our societies.

But beyond these individual trends, a much larger danger emerges: the possibility that due to the interaction between several of these destabilizing trends, the whole of our societal organization is thrown into disarray. We conclude that, rather than, as is usual, deal with developments in each domain separately, we need to consider them together, in a holistic manner, if we are to become aware of such interactions.

Next, in Section 2.3, we will show how, on balance, current trends in six major, highly interactive domains (Human capacity and demography, Decarbonization and energy, Food, biosphere and water, Smart cities, Consumption and production, and Digital revolution) are currently not, or insufficiently, contributing to sustainability. One of the world's major policy foci in the next thirty years must be to invert those trends in a sustainable direction, or when they are contributing to sustainability, to strengthen them.

We will conclude the chapter (Section 2.4) with arguing that by adopting a strategy of designing for change (rather than changing when in trouble) we could greatly improve our chances of achieving the SDGs.

2.1.1 Placing society at the core

After many years in which sustainability issues were principally the domain of the natural and life sciences, the social science community is getting seriously involved. Hence, sustainability is now viewed as a socio-environmental challenge, and much research is dedicated to the immediate relationship between societal and environmental dynamics. But we must go further and finally acknowledge that *the real sustainability challenge is societal, not environmental.* Societies define and shape what they consider their environments, what they see as the main challenges in the environment, and what kind of solutions they can try and offer. If humanity is to re-equilibrate with the environment, that will have to come from changes in mindsets, societal structures and human behavior.

Hence, *placing society at the center of the sustainability debate* is the next quantum jump that we have to implement in our thinking. This is reflected in the structure of Section 2.2: from people via institutions, technology, values and economics to natural resources. But, of course, there are many human societies on Earth, and these have different ways of perceiving and dealing with their environments. Each has developed over long stretches of time in a path-dependent co-evolution between perceptions, ideas, values, institutions and ways to interact with the environment. The socio-cultural diversity of human societies is profound and is an important aspect of socio-environmental relations. Yet, as the SDGs have been adopted as global goals, to be implemented by each country at the national level, we must try to discuss them at the global level as well as at that of the cultures involved.

In this chapter, which we see as a first step in a longer-term research process aimed at doing just that, we will confine ourselves to the global level, emphasizing existing trends and ways forward (Chapters 3 and 4) that are globally relevant. In subsequent work we will see how some of these trends are instantiated in different cultures and nations, and how, therefore, the exact way forward may differ in each instance.

2.1.2 From here to the future … or back?

To project into the future is, of course, fraught with difficulties. When life was slower, it did not matter so much as we had time for regular reassessments that could keep our systems functioning under changing circumstances. But with the acceleration of everything- innovation, communication, transportation, technology, etc., - that is no longer the case, and we must learn how to improve projections.

This can be done in two ways. Either one extrapolates from the present to the future, or one determines what kind of future is plausible and desirable (Bai et al., 2016) and then constructs a roadmap from the present to the desired future.

Whereas future(s) arrived at by taking the present as the point of departure are constrained by present-day thinking and existing trends, the second approach does enable us to conceive "out-of-the-box" futures, but it is more difficult to see how these could be realized.

The SDG approach is inevitably a hybrid attempt to link these two ways of conceiving the future. On the one hand, it projects a fundamentally different (sustainable) future, to be implemented differentially across countries, while on the other it assumes continued "progress" from the present to that future or futures. It takes the present as point of departure and yet focuses on arriving at a very different future (or set of futures). In doing so, it not only limits the range of visions that may be conceived for our future to those that can be extrapolated from our present, but it also ignores the possibility that fundamentally disturbing dynamics might unfold between the present and 2030, c.q. 2050, which could completely change the societal contexts in which the SDGs would be implemented.

The role of the TWI2050 project is to bridge that gap between the present and the future by developing different scenarios describing potential trajectories from present to future. Scenarios that take the possibility of fundamental changes in our socioeconomic and environmental conditions into account.

In the next section, we will therefore touch upon some major ongoing long-term trends that are likely to trigger events that will require fundamental decisions about the pathways we may take to achieve the SDGs.

2.2 A critical examination of some current trends

We have chosen to examine, at the global scale, some major current trends in demography, economics, finance, society and politics. Although each of these trends in itself has potential to trigger major tipping points for our current world system, *the importance of this examination is the fact that these dynamics are likely to interact, thereby creating an uncontrollable development that may change the world so much that 2030 and 2050 will be presenting a very different context from the present.* In that process the rapid evolution of ICT is a crucial factor, with consequences for almost all aspects of our current world order. *But it is important to emphasize that the underlying trends are not new – in some instances they go back centuries, in others 50 or more years.* They have gained so much momentum that changing them will be very difficult. *So, the major challenge we face is to understand such interactions and identify mechanisms that could orient them towards the future we want.*

2.2.1 People

2.2.1.1 Global demography and health

Figure 2.1 compares several recent population projections by the United Nations (UN) (probabilistic) and International Institute for Applied Systems Analysis (IIASA) (Shared Socioeconomic Pathways) to the end of the century illustrating the uncertainties in projecting so far into the future. Some scenarios based on rapid development show a peak of world population into the future, but noticeably not before 2050. Some others implementing a stalled development result in a continuous increase. This figure poses a fundamental question: will the current global population explosion continue, or not?

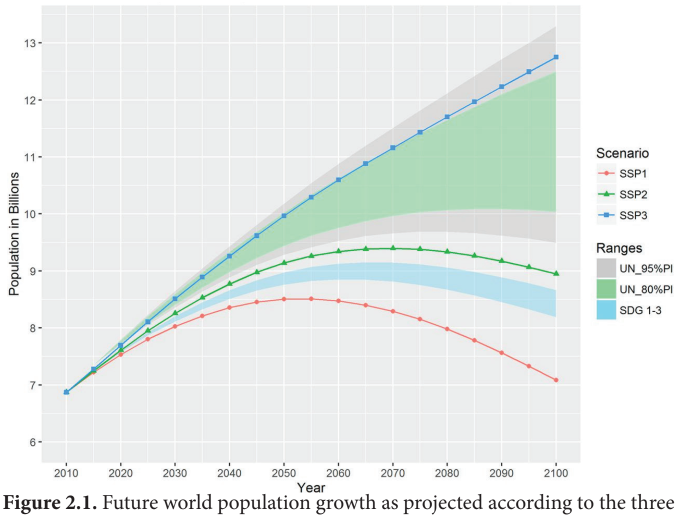

Figure 2.1. Future world population growth as projected according to the three SSP scenarios, the range of SDG scenarios presented here, and the probabilistic ranges given by the UN population projections. Source: Abel et al. (2016).

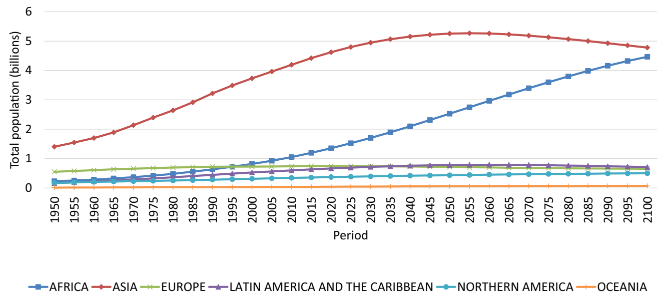

Figure 2.2. Population growth is very uneven. Population by region: estimates, 1950-2015, and medium-variant projection, 2015-2100. Source: After UNDESA (2017).

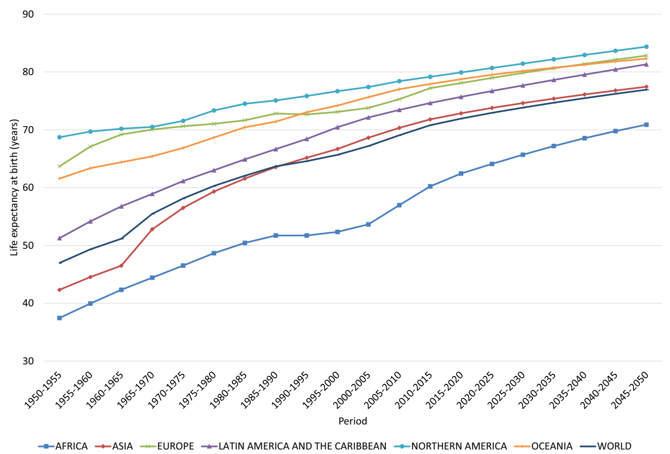

Figure 2.3. Life expectancy at birth (years) by region: estimates 1975-2015 and projections 2015-2050. Source: After UNDESA (2017).

It appears that with growing wealth in the developing world, the crude birth rate will go down as life expectancy increases (Section 2.3). A crucial question is, however, whether growth in wealth and decrease in birth rate will manifest themselves at more or less the same rates or not? Another question is how these processes will play out in different parts of the world. No one knows, but it is clear that 200 years of industrial economy have created important demographic discrepancies that may impact on global sustainability. Figure 2.2 shows that the increase in projected world population is uneven; Africa show major increases, Europe and other regions are projected to slightly decrease. Figure 2.3 shows how life expectancy at birth is also very unevenly distributed in ways that are similar to that of wealth.

Currently, in a number of developed countries, aging and a low birth rate combine to cause decreasing numbers of inhabitants of working age: Japan, China and Germany are examples. Others still have an expanding population due, for example, to important immigration (the US, Canada, Australia) but in a general political climate in which immigration is increasingly subject to xenophobia, those fluxes may well decrease. That will have an impact on the nature and size of their economies. On the supply side people will be replaced by automation, leading to unemployment, and this might negatively affect the demand side.

The opposite is the case for South East Asia and Africa, where birthrates are still higher and the working-age population will be growing for some time. There, economies will continue to grow, and one of the interesting questions that raises is whether this will also entail a shift in global power balance towards these continents.

That will in part depend on whether, and in how far, they will be able to develop their technologies and economies, as well as their institutions and legal systems. China has shown, over the past few decades, how this can be done.

Another fundamental characteristic of the current world, but with ancient origins, is the occurrence of large-scale migrations. Current research indicates that on a global scale, migration has not recently increased substantively, but at local and regional scales it has shifted demographics. According to the United Nations, during 2005-2050 the net number of international migrants to more developed regions is projected to be 98 million (UNDESA, 2017). Such regional migration is likely to further accelerate in the foreseeable future due to, for instance, climate change, sea level rise, and food and water availability. But there may also be increasing pressure towards migration for societal reasons, such as warfare, failing states, populism, ethnic cleansing or criminal violence. The counterpart may be a defensive reaction in developed countries, fed by local populism and identity issues, which creates more barriers to migration and globalization, as is now happening in Southern Europe and the United States.

We may therefore anticipate major cultural, social and economic challenges in the developed world as well as in the developing world wherever state control is not willing or able to prevent mass migration.

2.2.2 Institutions

2.2.2.1 Globalization and conflict

For five centuries the European (and later the Western) socioeconomic system has spread across the world. Initially this occurred through trade (1500-1800), then (1800-1945) through agricultural and mineral resource exploitation under military and administrative control, and since the Second World War (WWII) in the form of economic colonization. But since WWII, a counter-trend is also visible, in which ex-colonies gain independence, find their economic footing, and gain self-confidence in part through learning from developed countries. Now the Euro-American sphere is coming under increasing political and economic pressure. The rise in importance of the BRICS (Brazil, Russia, India, China and South Africa) countries is a sign of this trend, which is bound to be a source of uncertainty while the world searches for a new political organization.

An important underlying trend is that a reduction in the dimensionality of metrics (and awareness) of human wellbeing has emerged. Different cultures and populations now interact principally around the dimension 'wealth' when they judge themselves, compare among each other and transact exchanges. This has increased the emphasis on productivity and growth and has led to the over-consumption of natural and social capital in many regions. Other dimensions such as religion, community solidarity, art, culture, have decreased in importance as primary drivers of decision-making except among focused subsets of societies whose interaction creates 'hotspots'.

Current populist movements find their origins at least in part in the need to re-appropriate those multidimensional communal value sets, as was finely analyzed by Polanyi (1944) and members of his school in anthropology (Munck, 2005; Graeber, 2001). Elites have been able to make the transition towards a globalized society, whereas a very large majority of citizens worldwide has been left behind, focused on their local community and thus resistant to the reduction of the dimensionality sphere of their identity. This has shaped two 'deep' (second-order) fields of tension. Globalism poses a threat to the future of governance because it disenfranchises the vast majority and empowers a technocratic elite. But it also stimulates the emergence of identity issues, which are creating fields of tension between nations. Both trends are increasing the risk of (inter)national conflicts.

2.2.2.2 Our global governance system

The Treaty of Westphalia in 1648 and the Congress of Vienna in 1815 laid the foundations for the organization of the European nation-states and the philosophy that shaped it, based on *sovereignty* (the freedom of national governments to act as they see fit in their territories without outside interference), and a *balance of power* between states. That order collapsed in the 20th century when individual states pushed the system out of balance, leading to the two world wars and the collapse of several major empires (Haass, 2017; Kissinger, 2014).

After WWII, all efforts were directed at re-establishing stability, by creating a series of global institutions such as the UN and its agencies. This led to a more or less stable geopolitical order for another 40 years, thanks to the balance of power between the North Atlantic Treaty Organization (NATO) and the Warsaw Pact. But with the collapse of the Union of Soviet Socialist Republics (USSR), this order fell apart, both between states and within them. As the US military completely dominated the globe, competition shifted to the economic sphere; nations focused on internal economic development and increasing economic interdependence through closer trading relationships. Economic frictions were negotiated through the General Agreement on Tariffs and Trade (GATT), at the World Trade Organization (WTO), and by means of bilateral trade agreements.

With growing interdependency between nations that was the result of growing trade flows, the relationship between domestic and international dynamics came to the fore, recently eroding the sovereignty that was the basis of the bipolar post-WWII system and creating an unstable multipolar one. Regional 'hotspots' emerged across the world, where competition between regional players led to (potentially explosive) tensions of mixed economic, nationalist, religious, ethnic and tribal nature.

These trends seem for the moment on an ascendant path. We cannot, between now and 2030 or 2050, count on a global web of stable governments and have to envisage that the political world may look very different by that time.

2.2.2.3 Democracy and its values under pressure

The governance system of most developed countries is, since WWII, democratic. Individuals delegate their political power to an elected elite that makes decisions for a limited amount of time. This system works as long as internal tensions in societies can be worked through by discussion, debate or vote.

In most developed countries, *there seems to have been a connection between the adequate functioning of the democratic system and the rise of the consumer society,* leading to huge increases in use of raw materials, energy and human capital in the countries concerned, and our current sustainability challenges.

Currently, as material and social stresses increase, mainstream media and long-standing political parties are losing power, as is clear from the recent Brexit referendum, as well as elections in Europe and the United States of America. The vacuum has been filled by populist organizations that find their base in social networks and undermine the democratic system in four different ways: 1) accelerating the decline of political parties and other institutional forms of engagement, 2) weakening the legislative branches, 3) reducing a sense of social cohesion and 4) undermining democratic state competence. In some instances, this has led to hybrid democratic regimes which keep the trappings of democracy, including seemingly free elections, under leaders who control the election process, the media and the scope of permissible debate. This is currently a highly debated issue, and to illustrate it we have chosen a few, relatively random, examples (Edsall, 2017; Selian, 2003; Horrocks and Pratchett, 1995; Abramson et al., 1988).

Underpinning this process is the loss of alignment around sets of values more or less shared by people in the developed countries. The recent multiplication of sources of information enables subgroups in society to focus on a narrow set of sources for their information, leading to different conceptions of 'truth', 'signal' and 'information' and fracturing the overall alignment of societies ("people live in different bubbles").

2.2.2.4 The de-construction of communities

In his *'Great Transformation'* (1944) Polanyi distinguished between 1) "markets" as auxiliary tools to ease exchange of goods serving to maintain *social* relations - and 2) "market societies", in which the society becomes subject to the laws of the market, *subordinating the dynamics of society to the economic dynamics of the market's "invisible hand"*. As part of the Industrial Revolution (roughly from the 1830's to the 1850's), a fundamental transformation between these two approaches seems to have occurred in the UK, which then spread across the world as part of globalization. A financial, unidimensional economic logic was progressively dis-embedded from the wider, multidimensional, socio-cultural logic and grew in importance to the detriment of the latter (Ussher et al., 2018; Frieden, 2006; Graeber, 2001; Polanyi, 1944). Munck (2005) has posited that globalization is at the root of the destruction of social communities because it undermines the multidimensional value spectra that keep communities together. People need to both belong to a group, and to distinguish themselves as individuals within that group. In order to enable that, a community needs to have many conceptual- and value dimensions. Such *values are social creations* shaped in the social networks that constitute the context of individuals.

Whether one agrees with these arguments or not, the destruction of many communities, in the process of migration, urbanization and rural abandonment, agricultural efficiency-related reorganization and so forth, is a fact, leading to an erosion of the structures at the base of our societies.

2.2.2.5 Urbanization

Urbanization is a global phenomenon that has rapidly accelerated and spread across the world. The relative longevity of the built infrastructure may explain why urbanization has so far been the most persistent societal dynamic known to mankind. Fossil energy enabled the explosive global urbanization of the last century. Urbanization is therefore often seen as a major stabilizing trend for the future. But most of the predictions about urbanization, and in particular that by 2050, 68% of the world's population is projected to be urban (UNDESA, 2018), and possibly about 80-90% by 2100, are based on a linear extrapolation of the current dynamics. We are actually dealing with a complex and highly vulnerable system with many nonlinearities and unintended consequences, and hence, such a linear scenario is not appropriate. Food and water security challenges may well force populations to disperse from their highly concentrated agglomerations. The ICT revolution may undermine the need for spatial concentration of information and material processing that drove the need to live in cities. Climate change will exert pressure to increase transport costs and to reduce the use of bulk transportation, so that we may have to develop economies that are more regional, more local. Together such dynamics may very well upset the business-as-usual scenario for urbanization. In order to deal with that, cities may have to change their policies from "changing under pressure" to "designing for change".

2.2.3 Technology

All the above structural, long-term ongoing developments are likely to be impacted, over the next decennia, by the rapid developments of technology that have emerged from the Industrial Revolution and the lifting of the energy constraints on innovation. These are commonly summarized as the Nano-, Bio-, Information- and Communication (NBIC) technologies. The first two of these are still in experimental stages and it is therefore difficult to outline their potential impact on society. As far as we can see at the moment, the *devolution of information processing and communication to electronic systems is the most important driver to have a transformative impact on the near-term global future of our societies.* It drives a transition that we will not be able to cope with by simply becoming more resilient while remaining organized as we have been. The acceleration of information processing, driven by increasing interactivity, communication between more and more people in possession of more and more complex and effective tools for thought and action is causing unintended consequences of actions and decisions in a dynamic that is beyond our control. We have no sense at all of how to deal with the second-order changes this may be triggering.

2.2.3.1 Dis-embedding information

The ICT revolution is nothing new. It is the culmination of a process of knowledge acquisition that began when humans 'bent their minds around' the challenge of creating artifacts. It accelerated under the impact of the Industrial Revolution, which put virtually unlimited quantities of relatively cheap energy at societies' disposal. Thus, lifting the energy constraint on innovation set in motion an explosive development in technology and knowledge acquisition (and thus information processing) of all kinds, improving overall health, wealth and resource use wherever the social conditions were favorable, and notably favoring education.

Until the 1860s, matter, energy and information were embedded in each other, mostly being transmitted in language, in the form of artifacts, but also in the structure of customs and organizations. Writing was a major step in dis-embedding information by substantiating symbols with informational meaning onto a material substrate, and thus facilitating communication beyond immediate interaction, and beyond unity in time and space. Printing popularized this means of communication.

With the telegraph and telephone, *transmitting* information became possible in the form of pure (electrical) energy, reducing the cost of communication hugely. But this electrification did not extend to the *processing* of information.

Due to the territorial limitations of national governance, the increasing efficiency of information processing has enabled – and been driven by – the growth of the large multi-national corporations. It now spreads over much of the globe, accelerating the creation of a global *extraction-to-waste economy* (Steffen et al., 2015) contributing to an increase in wealth differentials, exponential growth of cities, dependency on the fossil energy industry, globalization and the consumption society. It also reduces the chances that outsiders can become insiders.

But as part of that trend, the global information processing network will itself become more accident-prone and sensitive to minor disturbances because of its growing interconnectivity (Helbing, 2013).

2.2.3.2 Electronic information processing

At the root of the current tipping point is the fact that, presently, information is *not only transmitted*, but also *processed* in digital form, enabling the semi-independent processing of information by machines, reducing the time and energy involved in information processing to (near) zero, and accelerating second-order change in information processing into a nearly exponential one. Coupled with a very rapidly accelerating algorithmic software evolution, the acceleration is such that societal information processing is no longer able to deal with it.[1] This has important social consequences. The people directly engaged in informatics have an enhanced opportunity to accelerate invention. But this group is proportionately getting smaller as the technology becomes more complex, whereas those outside that small community are left behind. That is profoundly affecting our societies' general capability to absorb change.

[1] As roughly calculated by Friedman (2016), technological innovation generations last some 5-6 years, while changing behavior in society to fully exploit these technical advances takes up to 15 years.

2.2.3.3 Changing relationships between society and space

During the last 200 years, the acceleration of our means of transportation (cars, airplanes) has reduced time needed for going to places and increased the frequency of displacements. The ICT revolution has accelerated interaction further by enabling anyone to share any information immediately across the world.

This has implications for the relationship between humans and space, as the transformation of 'spaces' into 'places' (locations 'created by human experience', cf. Tuan (1977)) is deliberately disabled. That could ultimately undermine our current reliance on spatially defined administrative entities such as municipalities, provinces, states and nations. Territoriality is not a 'natural' state of affairs, but one created over time by specific historical circumstances.

As people become increasingly 'place-less', will other, non-territorial modes of organization emerge? An experiment with such a novel organization is currently being carried out in Estonia, which accepts applications for e-residency from anywhere in the world. Were others to follow that example, location would no longer define the laws and statutes governing a person or firm's transactions, but the organization that guarantees the transactions would do so, wherever in the world it might be established.

2.2.3.4 The impact of ICT on time management

Central to the evolution of the relationship between the individual perception of time and its societal management are external, mechanical devices enabling an "objective" measurement of time. Since the age of sundials and hourglasses, larger and larger communities have delegated their time management to mechanical devices of increasing precision, so as to manage the explosion of interactions involved in their growth.

A dynamic relationship between the size of the flow of information processed and time perception seems to be confirmed by everyday experience: when an individual is very busy (processes a lot of information), time seems to be 'flying', whereas when information processing falls below a certain level, time is perceived to move very slowly. If such a relationship exists, then the growing volume of information processed would seem to relate to an increasing subdivision of temporal intervals in societal time management. Would this come to a point that only closer integration between people and computers can deal with societal time management?

2.2.3.5 Loss of control over information processing

The ICT revolution is progressively transforming "information processing without *central* control" into "information processing without *any* control". Until now there have always been nodes that controlled information processing to some extent, whether through enforcement, institutionalization, incentives or otherwise. Each node involved only a limited number of people (subscribers to a daily, or listeners to a radio station), and there were barriers to the flow of information between them (spatial isolation, differences in culture, identity, administrative organization, finance or other). That enabled each node to maintain its culture, align its members on certain values, procedures and institutions. The reduction in information - processing space/time that culminated in the internet, is removing these barriers, generating an explosive increase in horizontal information processing at all levels of society across the globe. This has made it much more difficult for societies to maintain their own identities. On the one hand, ideas and values now move very easily from society to society, while on the other the risk of social fragmentation has increased, as ideas within a society get increasingly differentiated.

2.2.3.6 'Fuzzing' the boundary between information and noise

One important consequence of this loss of control over information processing involves the status of 'information' itself. Numerous internet sites now proclaim to provide 'news' but launch egregious 'information' that has little relationship with commonly experienced realities. Deliberately or by default 'factoids' are presented as 'facts' *according to the worldview of the presenter*. Though that is nothing new – the rumor mill has always, in every society, had this effect – in the internet age it is much more difficult to find out how information has emerged, and what its relationship to the realm of phenomena is. *This undermines in many societies the distinction between signal and noise and the alignment of people around shared sets of values.* Over time this could fundamentally affect the existence of all social institutions because it obfuscates the boundaries between the institutional structure of our societal interactions and the surrounding stochastic chaos. Individuals would lose their alignment and compass, feeling lost and immobilized by indecision.

2.2.3.7 Big data and individuation

The capability to collect, store and process 'Big Data' in great detail is transforming our understanding of societal phenomena. Traditionally, in social science, conclusions were based on statistical generalizations around limited samples. We can now enhance resolution to deal with individuals separately, improving our understanding of many societal dynamics at the cost of hugely increasing the need for processing power. This is one of the trends driving High-Performance Computing.

In practice, this trend also enabled a major concentration of information processing, and thus political and financial power, in the hands of a very small group of corporations that use the data in completely opaque ways. Governments have difficulty limiting negative effects, protecting privacy, ensuring full transparency and thus re-establishing eroding trust. This field of tension is potentially a very destabilizing side of the 'Big Data' revolution.

2.2.3.8 Automation and artificial intelligence

Relatively recent advances in information processing have also enabled the automation of increasingly complex mechanical tasks. In the last thirty years, robots were specifically designed to perform relatively simple, monotonously repetitive tasks. But that, too, is changing. Very recently the combination of 'Big Data' with 'Cloud Storage' has laid the foundations for the development of contemporary artificial intelligence (AI) based on Machine Learning (ML). It programs the computer to recognize and identify patterns by analyzing very large numbers of data through approaches in which initial approximations of meaning are tested and refined many times until they come close to correct understanding (cf. 'fuzzy sets') (Zadeh, 1975). Such reflexive learning based on analysis of very large datasets enabled computing to conquer important new domains of information processing, including non-routine and relatively complex analytical tasks for example. It enables an ICT-based system to operate and adapt to changing circumstances with reduced or even without human control, as in the case of the self-driving car.

But AI is shifting from '*narrow*' (sets of specific applications for discrete problems) to '*general*' (multi- and cross-domain 'broad spectrum' applications). As this shift proceeds, *human-machine teaming* will grow in importance. This opens the road to employment opportunities that are not likely to disappear in the next few years. But filling these slots requires high levels of education and training people in the specific skills required.

2.2.3.9 Exploding connectivity among 'tools for thought and action'

The 'Big Data' revolution has exponentially inflated the volume of information that we can gather and process. But it also engendered an even more rapid increase in the connectivity between different signals and dimensions of the information processed. The ubiquitous availability of information from across the globe, and improvements in ways to search for, and identify, complementary components has accelerated this process further, enabling an important shift in the nature of innovation, from reliance on originating innovations (which open up a completely new technology) towards reliance on recombinant innovations (Strumsky and Lobo, 2015; Brynjolfsson and McAfee, 2011). A next step in this process is the development of the internet of things, connecting many of our everyday tools to each other so that they can interact, with or without human intervention.

2.2.3.10 ICT and education

Information technology is increasingly penetrating all aspects of our life and confronting all citizens whether they like it or not. It is currently applied for identity management by capturing biometrical data. According to the company Smartmatic (2018), the employment of their biometric technology helped to reduce the citizen registration time of Haitians from three months to a few days. Through the possession of an identification card, citizens are for example allowed to vote (Smartmatic, 2018).

In Denmark, a central person registration system is in place (Lifeindenmark.dk, 2018). Anyone who stays longer in the country than three months, or six months if EU/EEA citizen or from the Nordic countries, is obliged to register with the municipal authorities to receive their personal CPR number. It gives access to a range of services such as social security, handling taxes, open a bank account, conclude a phone contract, among others (Lifeindenmark.dk, 2018). However, strong cyber security needs to be provided, to protect from potentially damaging cyber attacks.

In the absence of increased, universal, "data-literacy" developments such as these will rapidly lead to major societal challenges. Retrieved data needs to be critically assessed to understand who provided the data, which method was used and what it conveys when embedded in a wider context. Our current education systems are not up to the task – relatively few people are educated to the necessary level, creating a very small elite in control of information, and many forms of education are themselves sub-optimal.

The transformation of education through the digital revolution takes many forms. Online education platforms such as Coursera (2018), or Khan Academy (2018) have become an established part of the education system and have allowed a larger public to engage and access information. Virtual reality simulation courses from i.e., Labster ApS (Labster, 2018), which allow students to learn a laboratory method before physically entering the laboratory, are currently in development.

Citizen science is another, complementary, new development, using technological innovations to engage the wider population in research. For example, the European Commission's Joint Research Centre encouraged citizens to report invasive alien species in their region by using a specifically developed app (Galiay, 2018; Tsiamis et al., 2017). In the United States, the Environmental Protection Agency (EPA) developed a toolbox with low-cost sensors for citizen scientists, among others, to collect local data on air quality, to help interpret it, as well as to compare it with data collected by regulatory stations (EPA, 2018).

But viewed overall, most educational institutions at all levels still practice teaching approaches that were developed many years (in some cases centuries) ago. Moreover, we need not only to focus on moving capacity building in technological research forward, but also to invest research time and money on discussing and reflecting how we will control such developments in ways to *maximize societal benefits (Tegmark, 2015).*

2.2.4 Economy

In many ways, the economy is both the best- and the worst-studied of the socio-environmental interactions. The best studied because there is a wealth of data available, but the worst studied because many formal macro-economic models used to explain observed patterns are insufficiently sensitive to detail, while in most instances they are dynamic equilibrium models unsuited to deal with the complexity of the dynamics underlying behavior (Beckert, 2016).

2.2.4.1 Finance

In recent years a very important, and growing, proportion of total financial capital is no longer engaged in the production of goods or services, but entirely devoted to speculation. Figures 2.4 and 2.5 show from two different perspectives how a larger and growing proportion of capital in the US is devoted to speculative than to productive activities.

The mobility of such speculative capital, and the fact that these huge financial means are controlled by fewer and fewer people and institutions, has had the destabilizing effect of contributing to a rapid succession of financial crises that we have seen in the last sixty years (Economist, 2014). Several aspects of this trend are so dangerous that we need to include them in our thinking about the future.

2.2.4.2 Trade, protectionism and investment flows

Several developed economies have exhibited a trend towards protectionism. While protectionist policies are often implemented under the pretext of protecting jobs or correcting bilateral trade imbalances, they ultimately restrict economic growth in the long run, since it inhibits trade in intermediate goods and the creation of value chain niches. The uncertainty produced by the threat of protectionism also hampers flows of investment in global capital markets, as it generates uncertainty regarding future economic growth (Erokhin, 2017). This is aggravated by trends in international aid, migration, climate change and geopolitics. Protectionism also threatens food sustainability by drastically shifting value chains and forcing replacement of staples and other foods with less sustainable varieties. Trade has a major role in stabilizing food prices, as well as shifting production from areas of high environmental risk to less risky areas (IFPRI, 2018).

The effects of protectionism in developed countries will be felt most acutely in the least developed countries (LDCs) (UNDESA et al., 2018). Many LDCs are dependent on external demand for commodity exports, as well as foreign aid for budget support (Timmer et al., 2011). In a closed world economy, many LDCs will continue to lag behind more developed economies, and this will have important ramifications in other sectors. LDCs will not achieve the economic growth required for sustainable development without a significant increase in investment. However, many of these countries are unable to attract the levels of investment they require due to institutional deficiencies, an over-dependence on commodities subject to fluctuation in prices, and a dearth of basic infrastructure to support fledgling industries.

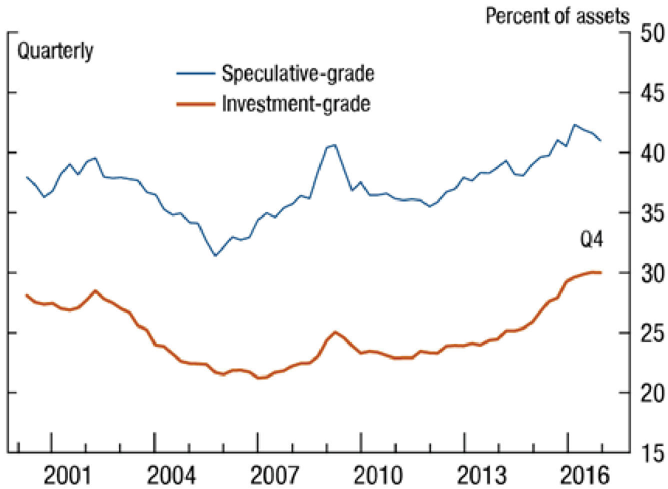

Figure 2.4. Gross leverage for speculative-grade and investment-grade firms, 2000-2016. Gross leverage is the ratio of the book value of total debt to the book value of total assets. Source: US Federal Reserve (2016).

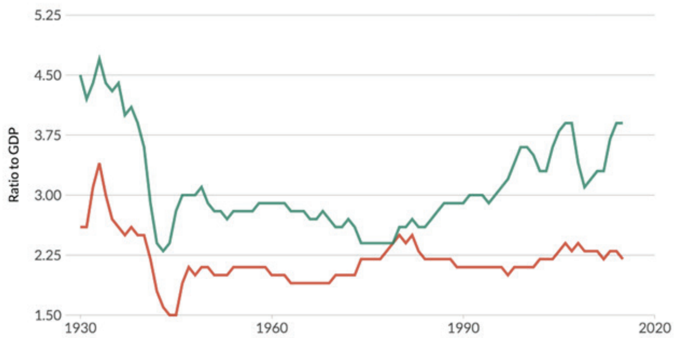

Figure 2.5. Fraction of total GDP (in the US) invested in production (orange line, without capital gains tax) and speculation (green line, with capital gains tax). The global recession of 2008 has depressed both trends, but the relationship is still the same. After: Washington Center for Equitable Growth (2018).

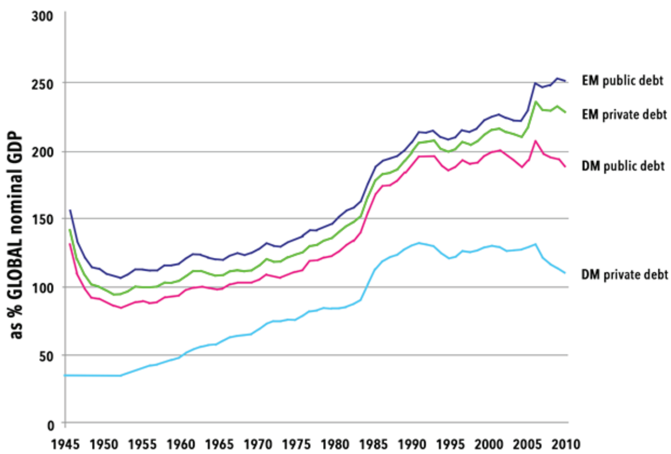

Figure 2.6. Private debt in developed and developing countries exceeds public debt. After: Hugman and Magnus (2015).

2.2.4.3 Debt

The rapid increase in global indebtedness (Figure 2 .6) is directly linked to overall financial and economic stability. As long as the world - and most countries - are on a growth trajectory this is not necessarily a problem as people have enough confidence that this debt will be reimbursed, and because inflation reduces the debt load.

We have to remember, though, that this whole system is *fiduciary*, and that if trust in it is for some reason or other undermined, it could collapse very easily, leading to major social unrest. There are many hair triggers that may cause such a collapse. We have seen how individual nations have seen trust in their financial systems collapse due to mismanagement or actual cheating (Argentina, Greece or Ireland are more recent examples). That is not affecting world financial stability as long as there are other economies that can serve as 'lenders of last resort' because they are bigger and in better shape. However, with the overall increase in debt level among both large and small countries this mechanism may itself be under threat. And because each crisis is countered by central banks with an increase in their debt levels, the underlying instability increases with each such event (Figure 2.7). Moreover, as an ever-larger percentage of gross domestic product (GDP) is devoted to interest payments, the proportion of GDP that is available for spending is reduced. Ultimately, this may limit the potential for further investment in infrastructure or towards the expansion of productive capacity.

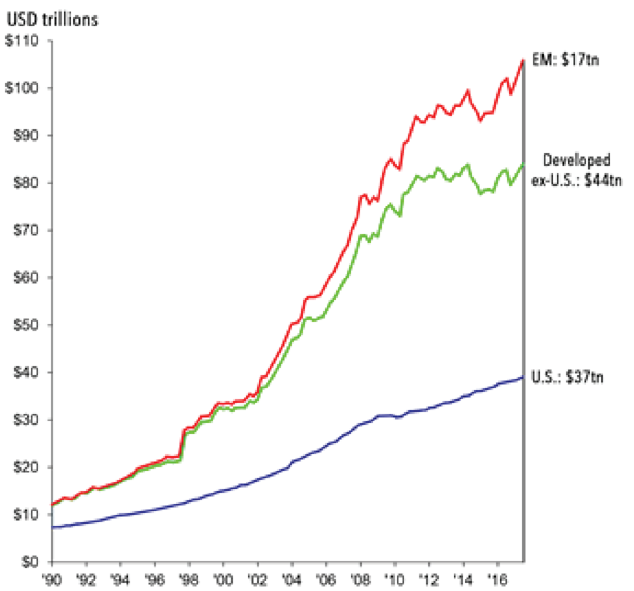

Figure 2.7. Public debt in the US, other developed countries, and emerging markets. After the 2007 debt crisis, public debt has increased rapidly, to level off (except in the US) after 2010. After: Durden (2017).

2.2.4.4 Aging population effect on savings, debt and pension systems

A major demographic trend with tremendous economic implications that represent a challenge for sustainability is population aging and its consequences on welfare systems in developed and developing economies. This includes pension and healthcare systems, in addition to a possible decrease in savings and investments (Bosworth et al., 2004).

The irreversible trend of an aging world population has profound implications on the sustainability of social welfare systems. In developed countries, an increased burden will be placed on public transfer systems, due to concurrent trends of a growing proportion of pensioners and a diminished tax base. However, the majority of the increase in the population above the age of 60 will occur in the Global South (UNDESA, 2017), where the elderly are less likely to have retirement savings plans or to be supported by public welfare systems, and instead depend on assets and labor income.

Without the means to support themselves in retirement, many of these people are susceptible to poverty. An aging world population also means that the share of non-communicable diseases in the global disease burden will grow, increasing pressure on countries' health expenditure, adding to the fiscal burden of government budgets.

Low productivity growth in developed economies in recent years has been explained by aging workforces, a slowdown in total factor productivity in the ICT sector, declining contributions of trade to economic growth, and stagnation in levels of educational attainment (Adler et al., 2017).

Between countries, global inequality has decreased globally in the last decade thanks to the contribution of China and India in their economic development process. As these and other emerging markets continue to grow, the economic hegemony of the United States and its Western allies will be gradually replaced by a multipolar world economy, in which India, China, Indonesia and Brazil become increasingly important economic hubs for financial services, manufacturing and innovation (Timmer et al., 2011).

However, this trend does not mean that economic growth will be evenly distributed. Many LDCs are at risk of continued vulnerability to economic shocks for reasons mentioned above. Their economic vulnerability is compounded by the fact that many of the LDCs are facing disproportionately high threats from climate change, have rapidly-growing populations, and also have weak governments and vulnerable security situations. These trends are inhibiting the ability of LDCs to bridge the gap between themselves and the emerging and developed economies. Without appropriate economic growth and investment, their populations may continue to grow at unsustainable rates, they will not be able to provide adequate education to their youth, and the coverage of health services will remain incomplete and fail to tackle preventable causes of morbidity and mortality (UNDESA et al., 2018).

2.2.4.5 Wealth differentials

The global economy has created excessive material wealth differentials between individuals by concentrating material wealth in a relatively small, if growing, proportion of the world's population (Figure 2.8). This has caused a steepening of the wealth disparities within and between countries in another very long-term 'deep' trend (Scheidel, 2017).

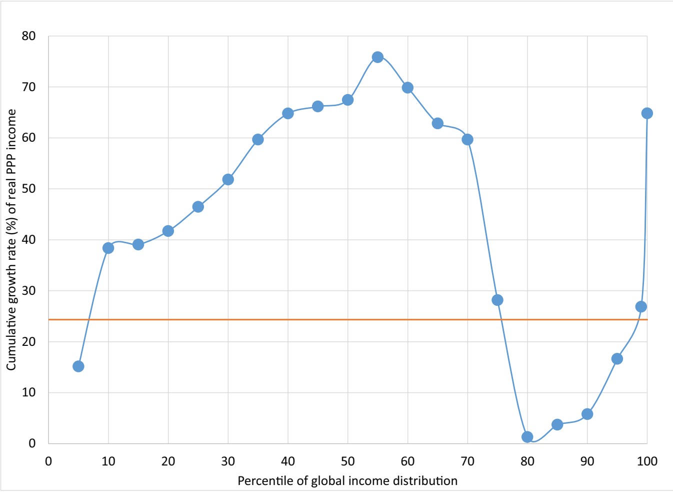

Figure 2.9. Global growth incidence curve, 1988-2008. One sees that below the 10th percentile incomes have grown very strongly, while incomes between the between the 10th and the 50th percentile incomes have grown substantially, whereas from the 50th percentile to the 80th, incomes have substantially declined. From the 80th to the 95th, they have grown some, and beyond the 95th, they have grown exponentially. Source: Licensed under CC BY 3.0 IGO by Lakner and Milanovic (2016).

If we look at the evolution of wealth globally (Figure 2.9), the so-called "elephant curve" (Lakner and Milanovic, 2016), representing the growth in average household income of each percentile group worldwide between 1988 and 2008, we see the combined effect of three trends: 1) rapid and substantive income growth for the poorest part of the world population, especially in developing countries, but starting from a very low base, 2) absence of, or low, income growth for the middle classes in the developed countries, and 3) rapid growth for the richest people in the developed and some developing countries (notably China).

Corlett (2003) shows that differences between countries' population growth rates and the selection of countries included in the statistics (notably Russia, Japan and China) accentuates some of the contrasts, but this does not fundamentally change the picture that the middle classes in developed countries have not seen any increase in real income in this period.
Figure 2.10 shows the evolution of the wealth gap over the last century (1900-2010). In particular, it illustrates how the 'big bang' of the 1980s, engineered by Reagan and Thatcher, has hugely increased the wealth gap in the English-speaking world, but much less so in continental Europe. The important lesson is the fact that, indeed, governments do shape markets, and would be wise to regulate them if they want to preserve social peace!

Education is one of the major differentiating factors in lifelong earnings capacity. The increased reliance of industry and services on ICT requires higher levels of education to deal with more and more complex tasks. Currently, this is one of the major barriers to optimize use of modern technologies. Turning now to some of the consequences of the wealth gap, Figure 2 .11 presents the relationship between income inequality and societal challenges in a number of countries worldwide, by projecting energy use (here taken as a proxy for wealth) against social progress.

The growing wealth discrepancy seems a manifest case of a societal planetary boundary that we are approaching or have already crossed. Some see it as an early warning sign of major social adjustments - in the developed nations as a protest against the squeeze of the middle classes, and in developing nations as a 'revolution of rising expectations' triggered by the fact that a small proportion of the population is getting (very) rich.

2.2.4.6 Innovation

When politicians and other people, talk about "innovating our way out of the sustainability conundrum", we would respond that the last two-and-a-half centuries of accelerating, undirected innovation in every domain of human life have actually caused our present sustainability predicament!

In accordance with their values, our Western societies will strive to maintain a degree of innovation. But their current "(technological) progress"-related orientation and its values should not blind us to the fact that for many populations, this may not be such a fundamental value.

Moreover, there are dynamics within our industrialized societies that could undermine our innovativeness. Summers (2016) argued that we may be reaching a plateau in the expansion of our global economies. Whereas his argument is purely couched in terms of economics and finance, it raises a more fundamental question: "Is it becoming more and more difficult to 'invent' novelty that has a major impact on value creation?"

One observes in the USA an overall decrease in return on invested capital (Figure 2.12) as well as a decline of entrepreneurship (Figure 2.13) that might be linked to an overall decline in the frequency of major innovations. Strumsky et al. (2010) show that between 1947 and 2006 the average number of patents per inventor has gone down from 2.4 to 1.7, while the number of people involved in a patent has gone up from about 0.6 to 2.5. If this trend continues, it will affect the growth potential of the economy.

2.2.4.7 From production to distribution

In the current system, our production economy derives its profitability from the gap between cost of production and perceived value of the product in the eyes of the consumer. That has driven the search for ever cheaper production methods worldwide, ever more efficiency in all aspects of production: human, financial, logistical, and technological. But worldwide limits to cheap labor, enabling large-scale industrial production, are looming. Although there remain pockets of relatively low labor cost, the profitability and existence of the traditional market-based production economy may come under stress.

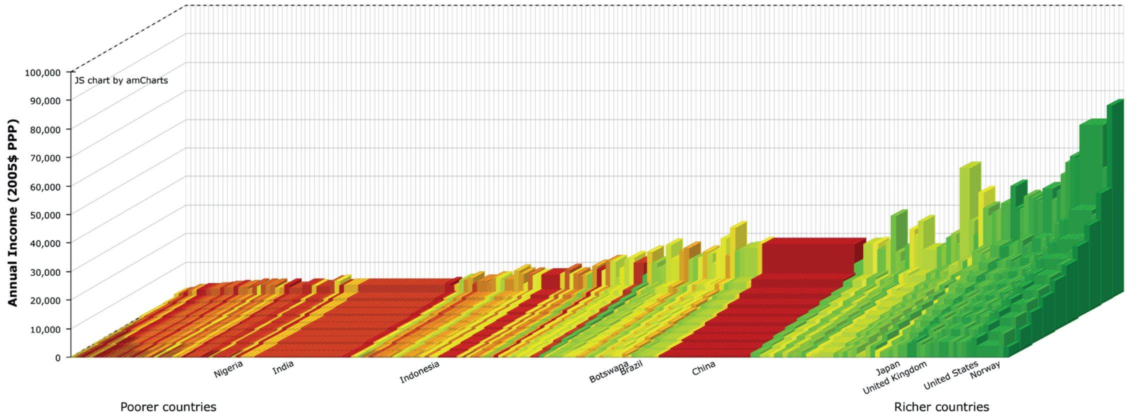

Figure 2.8. Worldwide difference in wealth distribution. Source: Blundell (2018) based on Sutcliffe (2004).

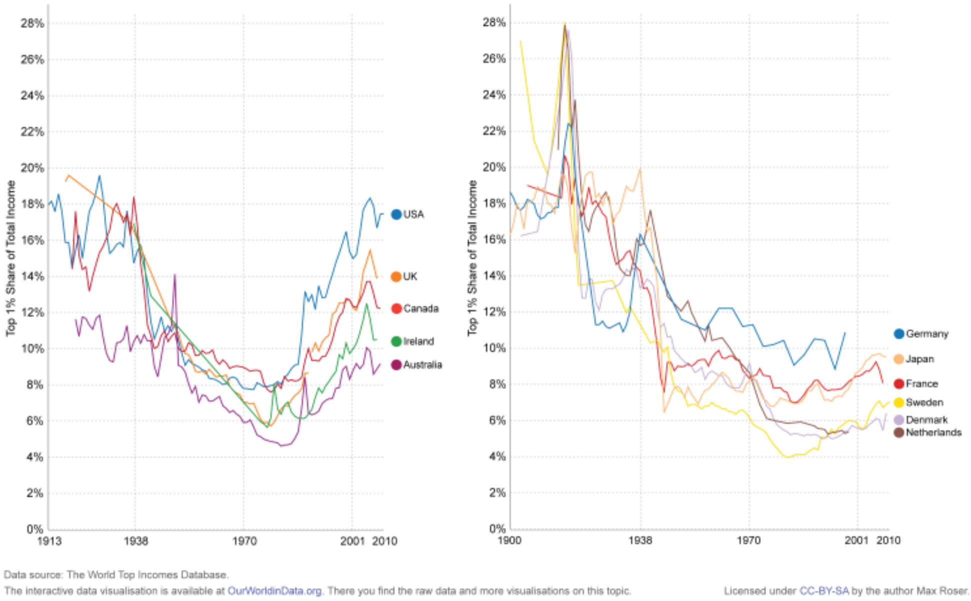

Figure 2.10. The evolution of inequality. The 1980s 'big boom' in the financial regulation has inverted the reduction of inequality in the anglo-speaking world, but at least until 2010 not in other parts of Europe. Source: Licensed under CC-BY-SA by Roser (2018).

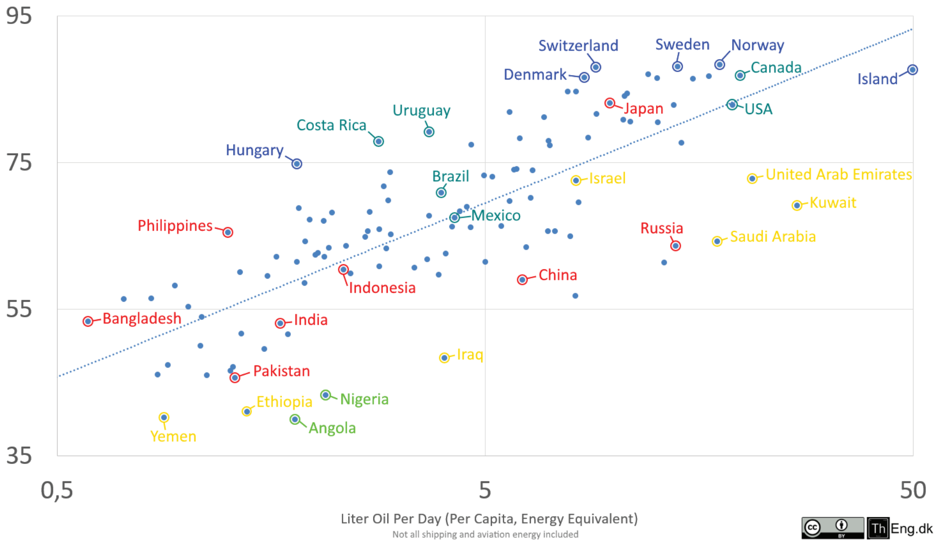

Figure 2.11. Social Progress Index vs Energy per country. The relationship between per capita energy use (here taken as a proxy for wealth) and social progress (an indicator combining life expectancy, math and literacy, infant mortality, homicides, imprisonment, teenage births, trust, obesity, mental illness, including drug and alcohol addiction, social mobility). Source: Wikipedia (2018), licensed under CC BY-SA 4.0.

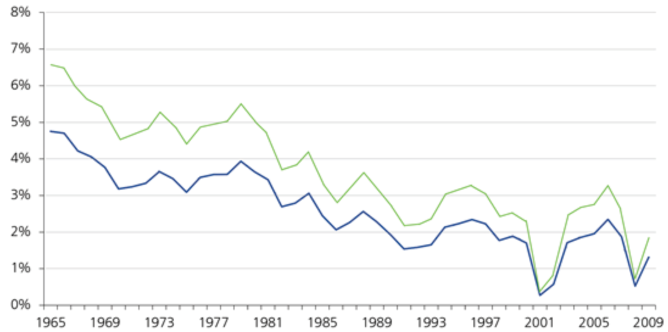

Figure 2.12. Evolution in return on invested capital in the US 1965-2011. The blue line represents the evolution of Return on Assets; the green line that of Return on Investment. After: Hagel et al. (2010).

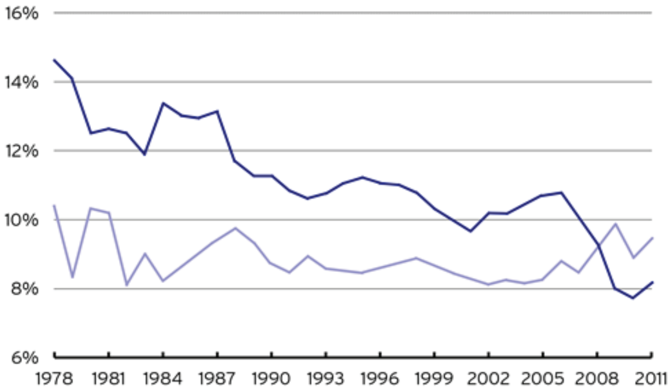

Figure 2.13. Annual new firm creations (dark blue line) and existing firm deaths (light blue line). After: Hathaway and Litan (2014).

Automation will no doubt mitigate this as robotics and AI replace human activities. Computers can increasingly associate diverse information into patterns, enabling them to respond appropriately to changing circumstances. For one, how to *use information can now be determined by computers,* enabling many more economic and other activities to be managed by them.

Economist and technologist Brian Arthur (2017) argues that this will bring us to a point where it is possible to produce enough goods and services for everyone through automation [if we can find ways to do so in environmentally sustainable ways]. This will trigger a major shift from an economy in which production of goods is the driver to one in which *ensuring general access to what can be produced* is the challenge. Arthur argues that this will bring about the following major changes:

- *The criteria for developing and assessing policies will change.* GDP and productivity are relatively good measures of the physical economy, but are much less effective in measuring the virtual economy.
- *The free-market philosophy will be less suitable* to the new situation because the focus shifts to more or less equitable distribution of value, away from the idea that the more is produced, the better it is.
- *The new era will not be an economic, but a political one*. The paradigm of the society at the service of the economy will have to be inverted to place the economy at the service of the society.

The transition is likely to cause a period of major upheaval, in which a number of social questions need to be answered: "How will we find meaning in a society where jobs no longer provide it?", "how will we deal with privacy in a society where every bit of information about everyone is concentrated in databases?", and "will we abdicate individual learning in favor of computer data and algorithms?" The changes and the upheaval will be as important as those that accompanied the Industrial Revolution, and may well take as long. Who knows?

2.2.5 People's experiences and Ideas

In this domain, we want to draw attention to two of the many potential changes that are currently observable, but which are only indirectly related.

2.2.5.1 The spectacularization of experience

Radio and television are among the earlier precursors of the full information technology. People did not have to be literate to peruse them, and their visual nature greatly enhanced their impact. Together, they hugely enhanced people's capacity to escape from everyday existence and live, albeit for a short moment, in a fantasy world. Guy Debord (1994) pointed to the fact that these media promoted the confounding of sincerity with authenticity and of emotion with emotional images.

As the tele-amusement industry developed, it habituated more and more people to live, at least in part, in a fantasy world. Over the past half century or so, this led to a fuzzing of the boundaries between fantasy and reality. In the 24 hour news cycle, this is achieved by presenting news in a simplified 'bite-size' form. Most websites follow the same pattern, leaving it up to the user to digest the full message or only a highly simplified version, leaving much to the viewer's fantasy.

The computer games industry is a direct continuation of this trend, but here the opportunity to escape into a fantasy world is no longer centrally controlled. In the process, *many dimensions of reality have been removed*. That has created a field of tension between people's experience and the real world, which in our opinion is, and will continue to be, of great impact on people's ideas and decisions.

2.2.5.2 Changes in society's 'value space'

In the relationship between observations, information and knowledge/understanding, values play an essential role. They distinguish between signal and noise, and align a society's members around certain information and resource flows, enabling them to communicate, collaborate and differ of opinion within a set of – often implicit – values. We call the society's 'value space' the total set of dimensions according to which a society attributes value to ideas, actions, institutions, material goods, etc.

Individual value differences are the result of the fact that people acquire their individual cognitive system ('world view') in different socio-environmental networks. Sharing a value space means that people's conceptions are sufficiently close to facilitate frequent constructive interaction. Within it, value differences allow individuals to create an identity and drive the information exchanges that are responsible for societal (and socio-environmental) change. Partaking in these information exchanges requires knowledge of the society's 'tools for thought and action' (language, customs, institutions and belief systems).

When a society is growing, it includes more and more people, knowledge and resources. That involves the construction of a set of utility functions, which initially will be relatively adaptable, but over time experience and complexity will expand and harden. A few terms come to dominate, leading to simplification and loss of dimensionality. Eventually the functions become brittle and can no longer adequately deal with change. The limits of the value space are reached. That generally results in an important increase in unintended consequences of actions, and in a reduction of the society's ability to implement new inventions. Is our current society at that point?

2.2.6 Natural resources

Due to the way in which the research into sustainability-related issues has developed, investigating natural resources and their relationship with society from the outside inward (for instance, having climate change, deforestation or carbon emissions as the starting point), the domains that fall under this heading have been extensively explored. As this section specifically aims to develop an inside-out perspective that puts the societal dynamics at the core and sees their impact on the environment as secondary, we will not contribute much to these domains, but only briefly ('pro forma') point to some of them. We use the energy and food sectors as examples. Both will be discussed more extensively in Section 2.3 as well as in later chapters.

2.2.6.1 Energy

Clearly, this topic has been looked at from all angles and disciplines, and there is very little to be added. Basically, *the societal dynamics that are driving our societies* have increased energy consumption from approximately 20 gigajoules (GJ) per capita per year at the beginning of the Industrial Revolution to approximately 80 GJ per capita per year now (Figure 2.14). Clearly this is very unevenly divided between the developed and the developing world. In the US, in 2013, average per capita consumption in the order of 290 GJ equivalent per year, while in India it was only about 25 GJ. Most of that serves in building, maintaining and running our material and institutional infrastructure. A growing need for energy is fundamental to the way in which the world is currently moving, and energy consumption, for political and economic as well as societal reasons, is not likely to decrease in the foreseeable future. Reduction of its climate impact is therefore essential.

As the sustainability conundrum has not been tackled at its societal root but mostly from the environmental perspective, core societal and social dynamics affecting the role of energy indirectly in the sustainability transition have thus far suffered from a lack of investment and attention.

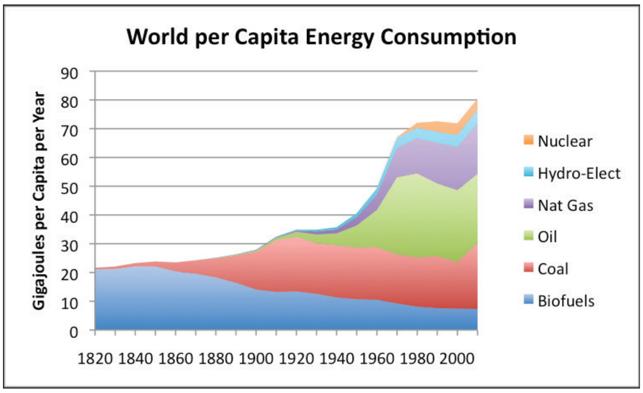

Figure 2.14. Evolution of per capita energy consumption since the Industrial Revolution. Source: Tverberg, Our finite World, licensed under CC BY-SA 3.0.

Without tackling the societal causes of that development, we will not attain a sustainable development for human societies on this planet!

2.2.6.2 Food (in-) security

We are facing a potential crisis in the provision of water and food for the world population that could very easily trigger major conflicts as a result of climate change, for example in Africa where the major powers are currently buying up land suitable for cultivation. Recent increases in food prices due to speculation are early warning signs that food security is becoming a worldwide concern. Figure 2.15 shows how, worldwide, food prices came under pressure because of one political act (stimulus of vegetal ethanol production) in one of the countries that exports a very large quantity of food (the US). It immediately led to food riots in Mexico! That tension is likely to grow further with the increase in global population and the demand of more and more non-vegetal foods**.** Currently we see that traditionally food exporting countries are beginning to import substantive quantities of food. The topic is of major concern, both scientifically and politically.

2.2.7 Conclusion: non-linear interactions

We have highlighted a selection of domains in societal dynamics where there are substantive chances for quantum non-linear change. The selection is of course arbitrary. We could have taken different themes and looked at them from different perspectives. They all concern the current or near-future state of long-term trends that are the cumulative result of earlier events and processes. But underlying, long-term path-dependent second-order dynamics are the drivers behind the trends involved.

These are very deeply embedded in our societal structures, have many feedback and anticipation loops among themselves and will prove extremely difficult to change. Almost all of them individually have potential "tipping points" in their trajectories – non-linear change points that are due to the unanticipated consequences of earlier dynamics.

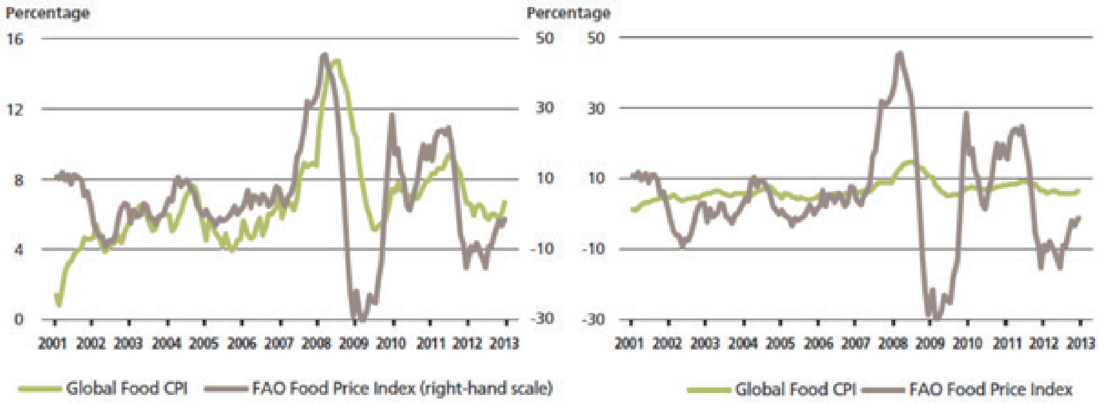

Figure 2.15. Food prices have recently spiked as a result of speculation and ethanol production to partly replace fossil fuel. Source: FAO (2017).

But that is not all. As mentioned at the beginning of this chapter, *the real danger for our societies is that a collision between several such non-linear tipping points will generate colossal disruptions, leading to a period of global chaos in all areas of human activity. Accelerated by rapid technological change, such as the ICT revolution, this may well occur on much shorter timescales than the occurrence of eventual natural (climate-related) tipping points. It is against this backdrop that the models in later chapters of this paper need to be viewed.*

This requires us to fundamentally change our perspective in order to understand and deal with the societal and socio-environmental dynamics involved. *We need to view them in their full complexity.* Our introduction of a long-term perspective shows that history matters – and that it is shaped by human decisions and events. At any time in the past (and the present), there were options among the directions that system dynamics could take. Some of these were adopted, others were not. Which trajectories were instantiated depended on a highly complex, multidimensional set of interactions between both societal and natural dynamics operating at different spatial and temporal scales (from the millennial to the instantaneous). Such interactions created, for different domains and different societies, path-dependent evolutions, in which the options the system adopted at any point co-determined later outcomes. The present-day manifestations of these path-dependent evolutions are the different cultures, technologies, institutions and values that we observe on the planet. One conclusion of this section is therefore that there are no 'planetary' solutions to the current sustainability conundrum – different societies will have to develop different ways forward. *There is no universal 2030 or 2050 tool box that fits all!*

The different dynamics involved can for long periods remain unobserved, then suddenly lead to unanticipated interactions among each other that rapidly change the structure of a system ('tipping points'). It seems to us that we are currently in an epoch where this is happening at a global scale, so that we are faced with a situation in which approaches that seemed thus far to enable us to understand and manage the various regional and local systems are no longer able to do so. We can no longer manage dynamics that, using our traditional perspective, are unmanageable. We can no longer hope to steer everything. Unanticipated consequences of earlier systemic actions are creating entirely novel, uncontrollable syndromes. In the face of these, the best we can do is to identify guardrails and to try and leverage dynamics so that they stay within bounds compatible with them. *We have to move from designing for control of system dynamics to designing for change in these dynamics!*

To do so, we have to open up our complete sets of societal norms, practices and values, all levels of our societal institutions, to fundamental change. *It is not only a question of our systems of societal and social-environmental governance, but also of our collective and individual 'truths', the nature of our social interactions, and (in short) everything we hold dear about our current way of life.* Many, if not all, among us will in one way or another resist that, and it will therefore be difficult to consciously achieve at a societal scale. But as we can observe already in many instances in the last decade or so, the emerging changes wrought by the information revolution will, willy-nilly, force us to adopt novel values, norms and behaviors. That process is driven bottom-up, as people adapt to the new technologies involved. It cannot be driven towards a particular set of goals or values. *Rather than attempt to do that, we will (have to) adapt our values and goals to the uncontrolled and uncontrollable dynamics involved!* Although that may seem very challenging, our long-term perspective points to the fact that humans have done exactly that under a range of different circumstances in the past. It is one of the characteristics of human beings that has enabled them to become the dominant species on Earth. But generally, they have not really done so until they were in a *'force majeure'* situation.

2.3 Turning the tide

In Section 2.2 we have introduced a number of long-term trends in current global societal dynamics, and how they might be impacted and accelerated by the current ICT revolution. We have concluded that the real danger is in the non-linear interactions between a number of these dynamics. We have then reasoned that any attempts to deal with these different dynamics individually will be insufficient in view of the intimate embeddedness of the various dynamics that are acting upon our societies and their environments. Instead, *we argue for a holistic approach to the sustainability conundrum and to the SDGs that emphasizes the many different dynamic relationships between dynamics that are usually considered singly or in pairs.* Now we need to turn our attention to what can, and should, be done to inflect current trends.

The challenges that we have presented so far prompt choices from among the following:

1) Trying to stop the current trends by attacking the roots of much Western "progress-related" thinking and the market-based system that it has generated, including the idea that technology will continue to progress in the direction it has taken in information technology, genetics and related fields.
2) Admitting that a de-growth scenario is at least for the moment impossible, and instead trying to mitigate the consequences or our current dynamics. That is what the carbon dioxide (CO_2) mitigation efforts are all about, and raises the question whether we could extend the same approach to other domains and what that would take, scientifically, politically and economically?
3) Try and reduce the vulnerability of different subsets of the overall societal dynamics by taking structural measures that constrain their envisioned negative consequences. One could describe that as placing guardrails along the trajectories of these dynamics, while searching for pathways to reach the SDGs (combining forward-looking and backcasting).
4) Move towards one or more scenarios that are rooted in an alternative, more stable and more sustainable vision of the future by trying to fundamentally change the mindsets that drive the current dynamic, and re-build our global societal systems based on such novel mindsets, values, goals and institutions.

Option 1) is difficult to achieve in view of the trends we have already set in motion. We are currently seeing, globally, in the Earth system community a distinct move towards option 2), supporting political efforts such as the protection of the oceans and the arctic, as well as civic initiatives such as that of the Transition Towns movement. That effort should evidently be continued, but it seems to be insufficient *from the perspective of the societal dynamics that are driving us currently.* The TWI2050 initiative is committed to achieving option 4) by backcasting from the TWI2050 normative goal rooted in the aspirations of the SDGs. The approaches to deliver option 4) are however still being developed and that is why we think for the time being investing simultaneously in options 3) and 4) is the most suitable way forward.

2.3.1 Selecting domains of action

In view of the complexity and breadth of the changes occurring, and those to be expected, any exploration of pathways to the SDGs must consider that the full complexity of social-environmental interactions discussed in the last section – from the basic values and world view of individual societies and cultures, to their ways of interacting, their institutions, their governance, natural resources use and so forth – will play out and impact on every aspect of present and future societies.

In order to move ahead, because we are not able to, at least for the moment, deal with the full complexity of the total systems involved, we have decided to focus on six exemplary domains that capture a large proportion of the current global, regional, and local dynamics that drive us away from sustainability, and which must thus undergo major transformations to redirect the global system towards sustainability:

- Human capacity and demography
- Decarbonization and energy
- Food, biosphere and water
- Smart cities
- Consumption and production
- Digital revolution

We have selected them because they are the domains that, together, to a large extent drive the overall current dynamic of our planet and the societies on it in an unsustainable direction. Hence, they need urgently to be tackled at every level of our

Figure 2.16. Six major transformations. Six domains that urgently need a change in direction. Source: TWI2050.

societies, from the global to the local, and for which we believe the tools to do so are available or will be available in the near future. We argue that transformations in these domains are both necessary and potentially sufficient to come close to achieving the SDGs by 2030 and to 2050 and beyond. But each transformation will require Herculean governance efforts and imply deep societal, cultural, and normative dynamics of change that we analyze in Chapter 4.

We emphasize that these domains are intended to be neither a new clustering of the 17 SDGs nor a "reduced form" of the SDGs and their 169 targets, but rather serve to describe systemic and integrative changes that are related to all SDGs as illustrated in Figure 2.16. Each of these domains relate to a large number of SDGs and can boost them holistically, focusing on their synergies. *They should be seen and studied as domains on which the processes outlined in Section 2.2 are impacting to a greater or lesser extent*, and in which major transformations must occur if we are to deal with the sustainability conundrum and realize the SDGs.

They are central to the six SDGs reviewed at the 2018 HLPF (SDGs 6, 7, 11, 12, and 15 as well as progress on 17). Arguably, they are not merely interlinked and interdependent with all SDGs, but they are at the center of any great transformation toward sustainability, and thus fundamental in "turning the tide".

2.3.2 How do these six domains cohere into a people-centered, holistic perspective?

Foremost, the six exemplary transformations give a people-centered perspective: building local, national and global societies and economies which secure wealth creation, poverty reduction, fair distribution and inclusiveness are necessary for human prosperity in any society and any region of the world. While these objectives may be pursued differently in different contexts some domains of action which appear to be of universal nature in this regards include: (i) institutions to enable and improve human capacities and capabilities, demography that includes secondary and not just primary education, adequate access to health care, fair labor markets, universal rule of law and means for managing aging societies; (ii) essential and strategic infrastructures of any local, national, global economy and society, such as: (a) energy; (b) food systems; (c) cities, settlements and mobility systems; (iii) production and consumption systems where deep transformations need to take place in order to create wealth and ensure good life and work, aiming at leaving no one behind and (iv) science, technologies and innovation (STI) that are essential for further progress toward achieving SDGs. This is a paradox, as STI has, in the past, created many negative externalities like transgression of planetary boundaries, but it is also indispensable for the transformation toward sustainability. STI drives one of the most fundamental disruptive changes in human history – the digital revolution which puts comprehensive AI at the center. A major challenge will be how to use the transformative nature of digitalization to create wealthy and inclusive economies and societies.

2.3.3 The current state of the six domains

Our first task, then, is to assess the current state of affairs in each of the six domains. In the next part of this chapter, we will see that either *ongoing developments are currently pushing away from sustainability*, or that *our attempts to do something have so far been insufficient to turn the tide*. In the following Chapters 3 and 4 we will focus in detail on developing approaches that might steer our global systems in the right direction. We expect that if they succeed in inverting the current developments that will consequently contribute to improve prosperity, social inclusion and sustainability in many societies.

In dealing with these domains and their interactions, we have to rely on research from very different disciplines, and, as importantly, research that is at very different levels of completion. In cases such as that of the energy dynamic, which has been subject to thirty years of intensive investigation, much more can be said than on the role of oceans, for example. But altogether, we believe that what is known about these six domains captures much of the dynamic that is currently pushing our societies towards an unsustainable future.

2.3.4 Human capacity and demography

Any global effort to achieve sustainability of our planetary systems, and in particular trying to reach the SDGs is closely related to the development of the global human potential – which we understand as the product of human capacities and human capabilities - in the next decades. By global human potential we thus understand the *integrated dynamic of human biological and social factors that determines the resilience and potential for change of our societies*. These are impacted by a wide range of factors, including human *physical wellbeing, education and appropriate social organization, as well as environmental, economic, technological, material and other factors*. They are also very different depending on local geographies, histories, and cultures. We will focus our analysis on the physical, biological and educational basis of human wellbeing. At the basis are, of course, the dimensions that determine the size and health of the population, and the level of education that it has.

2.3.4.1 Human demography

In 2018 the population of the world is growing at an average annual rate of 1.1%. This rate has been declining since 1965-1970, when it peaked at around 2.1%. The fact that world population growth is on the decline can be explained by the Demographic Transition Theory (Notestein, 1945). Eventually, according to this theory, all societies evolve from a pre-transition situation (stage 1) where fertility and mortality are unchecked and high, thus producing low population growth, to a stationary population (stage 4) when a society reaches low levels of fertility and mortality. This pattern is quite well established and exceptions have so far been of a temporary nature.

The main variability involved is the pace of fertility and mortality decline between stage 1 and stage 4. In most industrialized countries, where the transition was slow and happened over many decades, population growth was not dramatic. But in countries that started their demographic transition in the second half of the 20th century after many health-promoting advances had been made, mortality rates dropped relatively abruptly while fertility was kept high, leading to rapid population increase.

There are two major and important uncertainties involved. First, while it is very likely that the fertility will go down, it is difficult to know how long that will take and that makes a big difference. Whether for instance sub-Saharan Africa reaches replacement fertility in 2065 (the low-fertility variant of the UNDESA (2017)) or in 2100 (the medium variant), makes a difference of about 50 million in 2030, 210 million in 2050, and 1,200 million in 2100.

The second uncertainty concerns the number of children the population would have. This adds a further stage (stage 5) to the theory of Notestein, in which fertility is so low that generations do not replace themselves and the population starts declining (Lesthaeghe, 2014). Most industrialized countries seem to be on this path. For instance, in many Eastern Europe countries and in Japan, women have fewer than 1.5 children on average and fertility does not seem to recover to replacement level (e.g., Bosnia Herzegovina or Hungary).

Whether all countries currently going through the demographic transition will also experience this decline will be key to the future number of people on the planet. Some researchers contend that due to the arrival of contraception the fertility of women will be more and more determined by their individual preferences, following culturally anchored norms. We will need a few more decades to see whether some societies are trapped in such low-fertility situations (Lutz et al., 2006). But it is worth noting that when fertility decision processes become more and more individualized, providing financial and structural benefits to support childbirth is rarely crowned with success (see South Korea, and China) (Frejka et al., 2010).

However, although the uncertainties about the pace and the nadir of fertility seem to point to a world population that will eventually peak and diminish, this is not guaranteed. Moreover, the 21st century will witness continued population increase, concentrated spatially in the poorest socioeconomic settings.

2.3.4.2 Population health

Global statistics show that we are healthier and live longer than ever before. This substantial progress results from major advancements in public health and health care (e.g., health systems), including improved hygiene practices, health education, legislative changes, and technological developments, such as vaccination. Many recent health gains resulted from exploitation of natural resources, particularly for food and energy provision. Advancements in human health were critical for the human "great escape" out of poverty over the past 250 years (Deaton, 2013) as Figure 2.17 shows, leading to today's unprecedented levels of high global life expectancy and increasing survival of children under five years.

Despite significant overall progress, substantial improvements are still needed. Massive health inequalities continue to exist, and in some cases are widening, within and between countries. For example, average life expectancy varies between 50 years in Sierra Leone to 84 years in Japan, and children are 14 times more likely to die before the age of five in sub-Saharan Africa than in the rest of the world (UNICEF and WHO, 2017). Further, in recent years, life expectancy appears to be declining in the US (CDC, 2018) and the UK (Office for National Statistics, 2017).

Figure 2.18 shows how the burden of disease measured in disability-adjusted life years (DALYs) for men and women changed from 1990 to 2006 to 2016 (Gakidou et al., 2017).

Environmental, social, and political transformations can affect health directly and indirectly. We focus on critical dynamic trends already detrimentally affecting the health of specific populations: global aging, maternal and child health

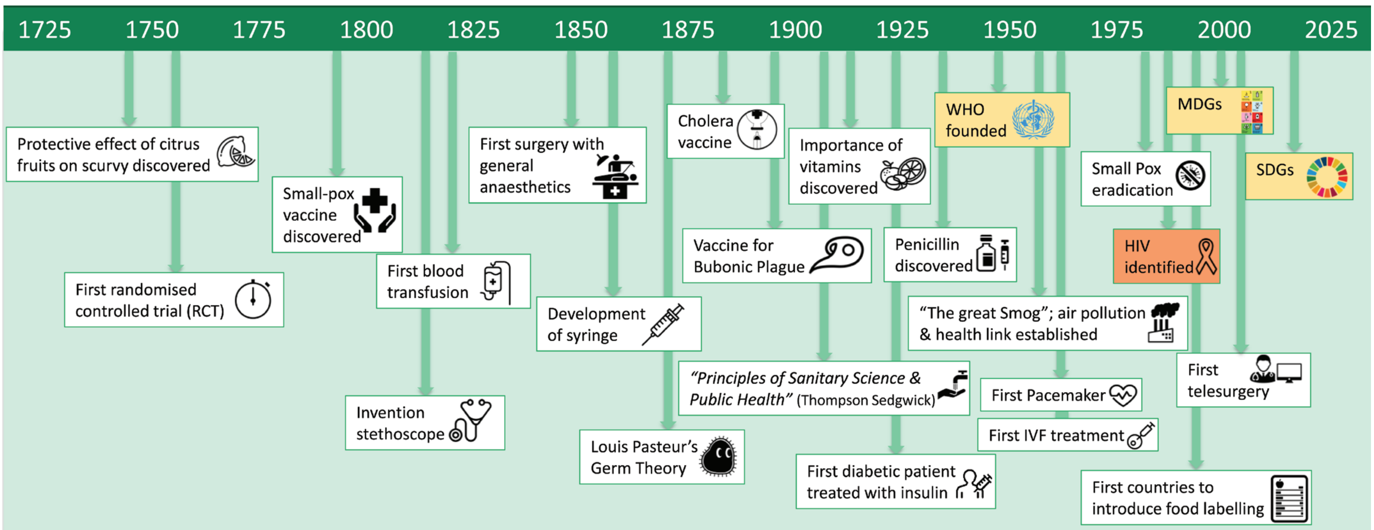

Figure 2.17. Major advancements for human health 1740 – today. Source: Provided by courtesy of Pauline Scheelbeek.

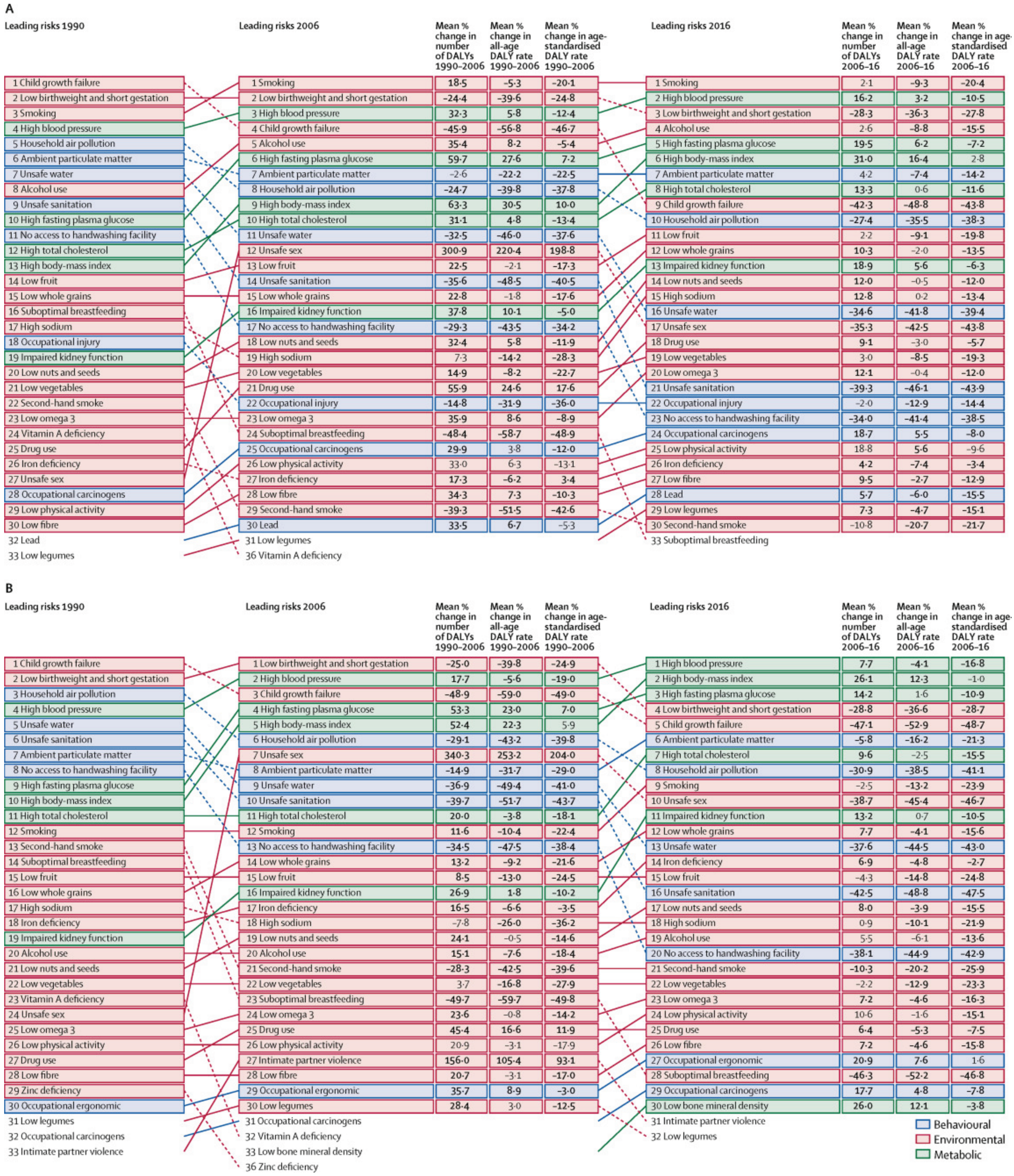

Figure 2.18. Leading 30 risk factors by attributable DALYs at the global level. Years 1990, 2006, and 2016 for males (A) and females (B). Risks are connected by lines between time periods. Behavioral risk factors are shown in red, environmental risk factors in blue, and metabolic risk in green. Source: Licensed under CC BY 4.0 by Gakidou et al. (2017).

improvements, emerging and re-emerging infectious diseases, the growing prevalence of non-communicable diseases, and urbanization. Several of the trends and health outcomes described are linked to global sustainability and could be negatively affected by climatic changes (Ebi et al., 2018). If not adequately addressed, these challenges will influence future health trajectories. Health is a cross-cutting issue throughout the SDGs, as changes in health impact the trajectories of other SDGs (and vice-versa).

Global aging

A key health challenge that countries around the world are beginning to and will continue to confront is population aging. As global fertility rates continue to decline and life expectancies lengthen, the median age is increasing throughout the world, although some countries, particularly those in East Asia and Europe, will be disproportionately affected (Lutz et al., 2017). Aging populations, particularly an increase in those over 75 years of age, will create sizable challenges for health systems due to greater burdens associated with non-communicable diseases and providing more frequent and expensive treatments for an older population, leading to increased overall health expenditure (WHO, 2015b). Although the retirement age is increasing in many parts of the world, people over 75 years of age are less likely to work, and could impose an economic burden on families and society (Bloom et al., 2015). Governments will have to grapple with how to address rising health care costs while continuing to fund other needed services.

Figure 2.19 shows the contribution of population growth and aging to the percent change in deaths and DALYs at the global level, 2006-2016.

Maternal, newborn, child, and adolescent health

Achieving a healthy world depends on improving the health of women, children, and adolescents. Investing in early childhood development is one of the best investments in boosting economic growth, promoting sustainable societies, and eliminating extreme poverty and inequality. Transforming maternal and child health will require efforts in the coming decades to increase education of women, address threats to the quality and quantity of our food and water, improve the quality and coverage of health systems, and promote nurturing care.

Maternal mortality (deaths due to complications from pregnancy or childbirth) fell by 44% between 1990 and 2015 (WHO, 2015b). However, this is less than what is needed to achieve the maternal mortality target for SDG 5 (Good Health and Wellbeing). Almost all maternal deaths are preventable. The lifetime risk of maternal death in high-income countries is 1 to 3,300 compared with 1 to 41 in low-income countries.

While significant progress in reducing childhood mortality has occurred over the past two decades, much remains to be done. In 2016, 5.6 million children under the age of 5 years died (excluding newborns within their first year of life), roughly 15,000 deaths per day (UNICEF et al., 2017b). Yet, other information confirms that most of these deaths were in the first year of life. More than half of under-5 childhood deaths were due to diseases that are preventable and treatable.

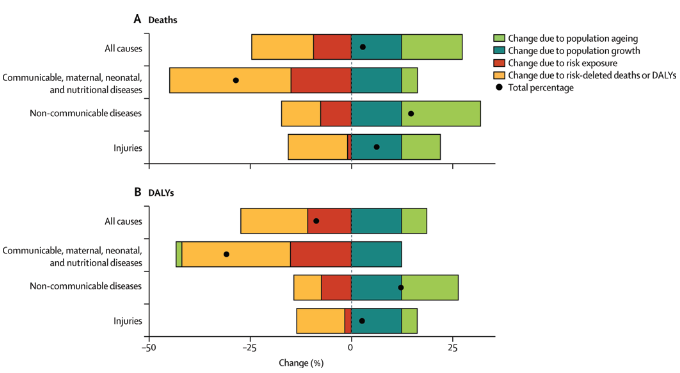

Figure 2.19. Percent change in deaths and DALYs at the global level. From 2006-2016, due to population growth, population aging, trends in exposures to all risks included in the 2016 Global Burden of Disease study, and all other factor. Source: Licensed under CC BY 4.0 by Gakidou et al. (2017).

During the past few decades, the world has taken significant steps towards improving child nutrition, with child stunting prevalence nearly halving from 39.5% in 1990 to 22.9% in 2016 (UNICEF et al., 2017a). Despite this progress, key challenges remain. In 2011, 1 in 3 people worldwide were affected by some form of malnutrition (including undernutrition, over nutrition and micronutrient deficiencies), 50 million children suffered from acute undernutrition (wasting) and 3 million children died from hunger (Horton and Lo, 2013). All aspects of food security will potentially be affected by climate change, including food access, utilization, food quality, and price stability, challenging continued progress on reducing undernutrition (Porter et al., 2014).

Most childhood diarrheal disease results from inadequate access to safe water and improved sanitation. It is estimated that 1.2 billion people gained access to piped water supply between 2000 and 2015 (UNICEF and WHO, 2017). There are still around 2.3 billion people who do not use improved sanitation and 844 million who do not have access to improved water sources, concentrated among rural populations with fewer resources and among fragile states (UNICEF and WHO, 2017). Moreover, in low-income countries, almost 90% of sewage is discharged without any treatment and some countries also continue to release wastewater to the environment without sufficient treatment (Baum et al., 2013). These practices increase the risk of childhood diarrheal disease.

Emerging and re-emerging vector-borne, zoonotic, and other infectious diseases

The radical transition in the contribution of infectious diseases to population health is one of the hallmarks of the 21st century. The global burden of infectious diseases has likely never been lower (Figure 2.20), and progress indicators across a range of key infectious disease categories continue to climb (Figure 2.21).

Despite these positive trends, infectious diseases continue to present a serious global health threat. For example, more than 1 billion cases and around 1 million deaths occur annually from vector-borne diseases alone (Campbell-Lendrum et al., 2015; Kilpatrick and Randolph, 2012), and the incidence, impacts or geographic range of several high impact diseases have increased globally (e.g., dengue, zika) (Stanaway et al., 2016). Additionally, the rate of novel disease emergence has grown (Fisher et al., 2012; Jones et al., 2008). Many of these increases in risk have been linked to a range of large-scale and rapid environmental and socio-demographic changes that have occurred in recent decades. These include climate change, land-use change such as deforestation and agricultural expansion, social and development trends including increasing international travel and trade, and widespread use of antimicrobials (Semenza et al., 2016).

Climatic changes have affected some infectious disease vectors or reservoirs, and in some cases have contributed to a rise or redistribution of infectious disease risks. The dramatic rise in dengue cases in the past few decades, for example, may be at least partially linked to improved environmental conditions for disease transmission or to increases in the geographic range of vector populations (Watts et al. 2017). Given that warming of nearly 1.5°C above preindustrial temperatures is projected to occur by about 2030-2040, increases in the burden of climate-sensitive health outcomes are very likely, with the magnitude and relative burdens dependent on the extent to which proactive and effective adaptation policies and measures are implemented (Ebi et al., 2018). In other cases, climatic changes are likely to have reduced disease risks as conditions suitable for transmission, vectors, or reservoir hosts are pushed beyond their climatic optima (Escobar et al., 2016). Determining the balance and geographic distribution of increases versus decreases in disease risk attributable to recent and projected climatic changes is an important scientific challenge for the Anthropocene.

Major environmental and social pressures and challenges embedded in the SDGs could also directly or indirectly influence infectious disease risks. Ongoing changes to food production systems, including intensification and pest control, are contributing to antimicrobial resistant strains of pathogens that are poised to reverse a long period of gains in intensive disease control (Holmes et al., 2016). Urbanization, while typically associated with improved health outcomes, can contribute to rises in some infectious disease risks (Tian et al., 2018). Land-use change for agricultural and socioeconomic development (including urbanization and road networks) will continue to drive contact between disease hosts/vectors and humans, resulting in yet further opportunities for disease emergence and spread (Murray et al., 2016; Jones et al., 2013). However, such trends could be partially offset, as vectors and hosts themselves become casualties from habitat loss or fragmentation (Cable et al., 2017).

Moreover, increa sing globalization – in both passenger travel and international trade – has increased the likelihood of country-to-country spread of infectious diseases. At best, these processes will produce repeated disease introductions, sustain or promote transmission of endemic infections, and catalyze limited, albeit unpredictable, epidemics (e.g., 2014 Ebola

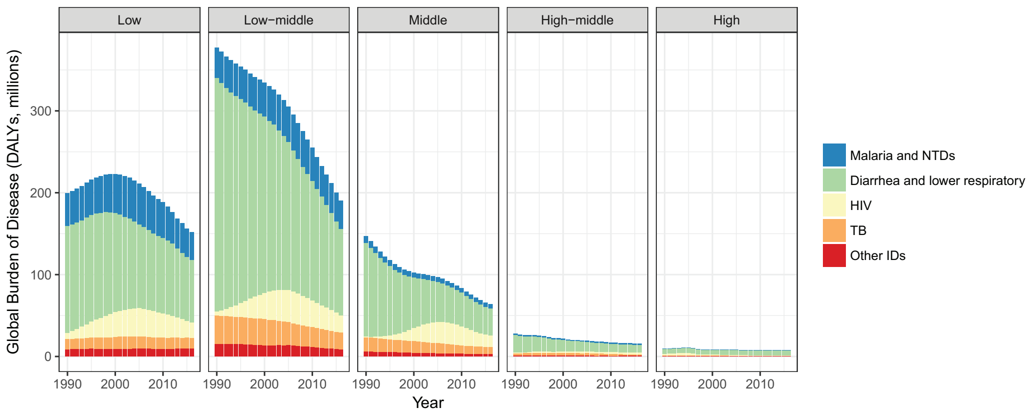

Figure 2.20. Breakdown of the proportion of the global burden of infectious diseases (as measured by DALYs) by income category and cause. Source: Provided by courtesy of Kris Murray / Imperial College London. Data source: Institute for Health Metrics and Evaluation, University of Washington.

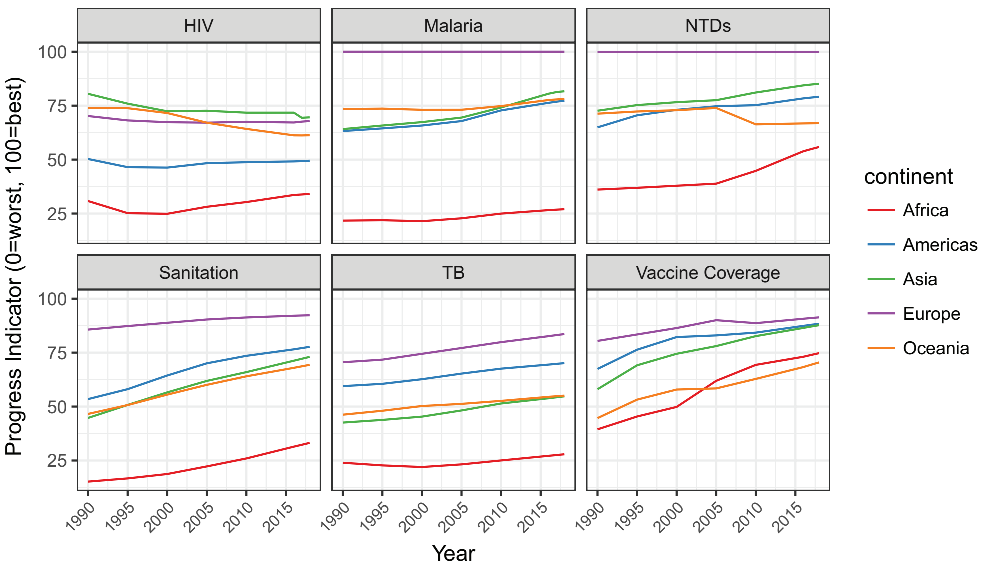

Figure 2.21. Trends in selected infectious disease progress indicators 1990-2015 by continent. Source: Provided by courtesy of Kris Murray / Imperial College London. Data source: Lim et al. (2016).

outbreak). At worst, they could help facilitate a global pandemic (Morse et al., 2012).

Increasing prevalence of non-communicable diseases

Non-communicable diseases (NCDs) include an array of serious health conditions, including cardiovascular diseases, cancers, diabetes, and chronic lung diseases. In 2015, 70% of deaths worldwide were due to NCDs, including 45% from cardiovascular diseases, and 22% from cancers. Over three-quarters of NCD mortality occurred in low- and middle-income countries, with about 48% occurring before the age of 70 (WHO, 2015b). This results in a 'double-burden' of disease, with high rates of communicable and NCDs in lower income countries. Major risk factors for NCDs include the environment (e.g., air pollution, Landrigan *et al* 2018), older age, unhealthy behaviors (e.g., poor diets, tobacco use, alcohol consumption and lack of physical activity), and metabolic factors (e.g., high blood pressure, obesity, and high blood glucose), often also related to diets.

Despite the world producing enough food from a caloric intake perspective, the food system is failing to deliver nutritious and healthy diets to all. Global diets are rapidly shifting towards processed and animal-source foods. Dietary factors now account for eight of the top twelve leading causes of death globally. Consumption of animal- source foods is increasing, which, combined with excess food consumption, is resulting in greater natural resource use than is needed for healthy, balanced diets (Aleksandrowicz et al., 2016; Green et al., 2015). The number of overweight/obese people in low- and middle-income countries more than tripled between 1980 and 2008: from 250 million to 904 million (Keats and Wiggins, 2017).

Urbanization

Population growth in recent decades has been concentrated in cities, with more than half of the world's population now living in urban areas (UNDESA, 2018). On average, urban environments may provide net benefits for health and wealth (an 'urban advantage') because of factors such as improved access to services (including health care, employment and education), better sanitation, and lower levels of malnutrition. However, rapid urban development has also resulted in a wide range of social and environmental problems. In some regions, most notably sub-Saharan Africa, urbanization has not been accompanied by significant economic development, with negative effects on health. Health outcomes in areas of urban disadvantage, particularly in urban slums, may be much worse than in other urban areas (Ezeh et al., 2017). Moreover, heat islands (areas of higher temperature associated with the built environment) are associated with adverse health outcomes. Greater urban sprawl may exacerbate these effects (Stone et al., 2010), although effective planning and urban design that emphasizes green spaces can mitigate these challenges (Kleerekoper et al., 2012).

Summary and conclusion

The status of population health and health systems in 2050 will depend on the interactions in the intervening decades among the trends discussed in this and other sections. Focusing only on health trends without considering trends in agriculture, demographics, land use, freshwater quality and availability, technology development, and other factors would provide a misleading picture of what is needed in order to improve health over coming decades. Understanding the implications of the interactions and magnitudes of these trends for health requires systems-based projections. Effective, proactive policies and measures, and increased investment in research, development, and implementation could lead to continuing improvements in health.

2.3.4.3 The education challenge[2]

Which means exist to influence the size of the human population? Scientific findings tend to demonstrate that formal education has a role to play in influencing both fertility and mortality patterns (Goujon, 2003). Formal education has an important impact both on the fertility of women and on the mortality of children born to those women (Jejeebhoy, 1995). Girls who go to school are exposed to the environment and society outside their own household and their neighborhood, breaking their isolation. There is thus a large difference (up to two children on average in Kenya and in the Dominican Republic) between the number of children born to a woman who has been to primary school (even if she has not completed all grades) and a woman who has never been to school. If girls stay in school, they will delay marriage and hence the onset of fertility. Furthermore, having an education increases the chance of finding employment outside of the house and therefore increases the opportunity cost of having children.

Moreover, the more education a woman has the more likely she is to use modern contraceptives, and space the birth of her children. By increasing her autonomy, education will increase her say in household (including fertility) decisions. Education is one of the most influential factors causing fertility to no longer be a given, but within the calculus of choice of couples, particularly women. Figure 2.22 shows the difference in the number of children of women with studies beyond upper-secondary, and those born to women who have never been to school (or less than a year). Differences are larger in sub-Saharan Africa and can exceed four children as in Angola (a five-child difference), Mozambique and Democratic Republic of Congo.

While levels of educational attainment influence the demographic behavior of people, population increase has also been detrimental to education expansion in many parts of the world. First of all, as a result of population growth, the population of children of schooling age has increased, but not everywhere, as can be seen from Figure 2.23.

[2] This section is largely based on the entry of Goujon, A. V. 2018. Human Population Growth. In: Fath, B. (ed.) Encyclopedia of Ecology. 2nd ed.: Elsevier.

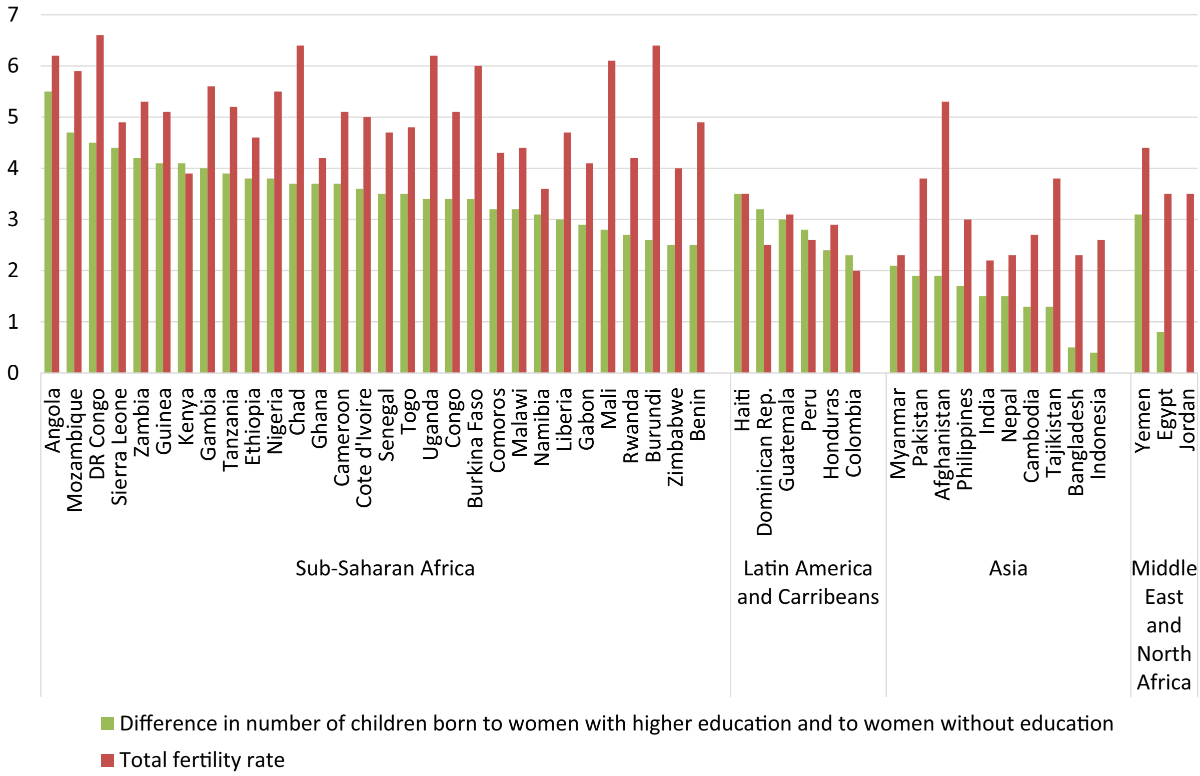

Figure 2.22. Difference in the number of children born to women with a higher education and to women without education and total fertility rates. Selected less developed countries, since 2010. Source: Goujon (2018).

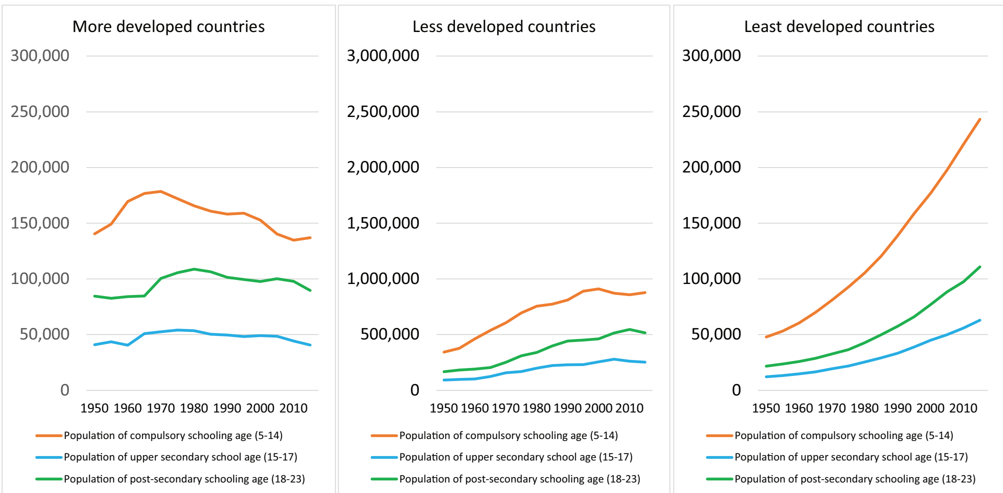

Figure 2.23. Absolute population (in thousands) of schooling age. Compulsory education (5-14), upper-secondary education (15-17), and post-secondary education in more developed countries, less developed countries (excluding LDCs) and LDCs. Source: Provided by courtesy of Anne Goujon / IIASA. Data Source: UNDESA (2017).

In more developed countries the population of schooling age, whether at the level of compulsory schooling (usually completion of lower secondary education) or post-secondary schooling, has been diminishing or stagnating in the most recent decade. However, in the LDCs, the population of compulsory schooling age has increased dramatically, more than five times since 1950.

2.3.5 Consumption and production

2.3.5.1 We are running out of natural resources

One major challenge associated with moving toward sustainability in production and consumption activities is the high and rapidly growing use of natural resources (e.g., materials, energy or land) required in the process. Without dealing with this issue, sustainability cannot be attained, and neither can the relevant SDGs. The focus in this section is on other materials (raw materials, their transformations into intermediate and final products, as well as wastes, emissions and recycled materials), but energy and water are also considered from their resource efficiency dimension, whereas land is dealt with in more detail in other sections. Methods to trace these processes include material flow analysis (MFA) developed in Ecological Economics, Industrial Ecology and Social Ecology (Krausmann et al., 2017a; Haberl et al., 2016; Pauliuk and Hertwich, 2015; Fischer-Kowalski et al., 2011; Ayres and Simonis, 1994). High use of physical resources is associated with depletion of non-renewable resources, over-stretching of natural systems to generate renewable resources (e.g., biomass/ land use), pollution, area demand (e.g., of infrastructures) and many other potential unsustainable systemic effects discussed below.

There exist many strategies to tackle the problem of natural resources by raising the efficiency with which materials are used, a strategy often called "eco-efficiency", "material efficiency" or "decoupling of physical and monetary growth" (Fischer-Kowalski et al., 2011; Steinberger and Krausmann, 2011). Essentially these efforts aim to raise the output of services and products while reducing the volume of raw materials required, and hence the adverse sustainability impacts of rising raw material use. This would require more efficient production systems (agriculture, industry, etc.), but also more efficient systems to convert physical products (e.g., final energy) into the required services (e.g., comfortable living spaces) and might even reconcile GDP growth with reduced resource use and environmental impacts.

However, even though material efficiency has generally been increasing over the last century, and in particular the last few decades, the extraction and use of raw materials is growing unabatedly, although now at a lower rate than GDP. This is a phenomenon called "relative decoupling" (Steinberger et al., 2013; Worrel et al., 2016). Many scholars today lean towards believing that eco-efficiency, although it has its undoubted benefits, will not be sufficient to "bend the curve" – in other words, *the "gospel of eco-efficiency" may be good, but most likely not good enough (Martinez-Alier, 2003).*

2.3.5.2 Developing a new approach to resource use measurement

Huge efforts have been expended to quantify and analyze material flows and their relation to GDP, technology development and other important drivers. This is rendered difficult by the fact that a substantial part of these resource flows serves to build up socioeconomic material stocks (often called "in-use material stocks") such as buildings, infrastructures, production capacities, machinery, etc. Indeed, the share of all material inputs (including food, fossil fuels, etc.) humanity puts in such in-use material stocks has increased from around 20% in 1900 to over 50% today (Krausmann et al., 2017b).

Including stocks into the picture is hugely important for a host of reasons, for example: 1) stocks transform resources into services. For example, crude oil or electricity does not allow one to go from A to B, only when coupled with a suitable infrastructure (rails, railway stations, trains, etc. respectively refineries, roads and cars) they can provide the service. 2) Building up, maintaining and using stocks requires very substantial amounts of materials. 3) Stocks create dynamics and lock-ins that last long and are difficult to change, e.g., transport infrastructures (e.g., railroads vs. highways, heating of buildings, transport demand resulting from settlement patterns vs. location of workplaces, etc.). 4) Stocks form structures influencing social organization, the organization of production and consumption activities (including work etc.), mobility of people and goods, and thereby shape social institutions, practices and values. Moreover, most such stocks result from investment decisions that are negotiated in the social, political and economic arena, so they are in principle amenable to be changed through strategic decisions (Chen and Graedel, 2015; Hertwich et al., 2015; Weisz et al., 2015; Pauliuk and Müller, 2014).

2.3.5.3 But this perspective only sheds a starker light

Including stocks and services in the analysis of the societal metabolism, respectively the physical economy, allows us to substantially enlarge and strengthen the current strategies focused primarily or even exclusively on "decoupling". It results in what has recently been called "stock-flow-service nexus" (Haberl et al., 2017; Weisz et al., 2015; Pauliuk and Müller, 2014). This approach aims to provide sufficient high-quality services to human societies in relevant domains (e.g., food, energy, shelter, mobility, communication & data services, etc.) while reducing flows of material and energy through better stocks (more efficient, based on more sustainable materials, resource-saving spatial patterns, etc.). This approach recognizes that indicators such as GDP may be as much a problem as a solution (Fleurbaey, 2009), and therefore maximizing GDP might not be compatible with a sustainability transformation (Kallis et al., 2012; Van den Bergh and Kallis, 2012). This approach is closely linked to discussions on how to achieve a good living for all within planetary boundaries (O'Neill et al., 2018; Rao and Min, 2018; Brand-Correa and Steinberger, 2017).

Rather than shed a dominantly positive light on current dynamics, this approach also *demonstrates limitations of useful and currently prominent strategies to raise eco-efficiency and reduce pressures on resources, for example the circular economy*. As most resource flows end up in stocks, and much of the remainder is used dissipatively, e.g., for food and energy, the potential to close material loops or cycles is limited (Haas et al., 2015), at least as long as material stocks are growing in 1:1 unison with GDP, which has been the case over the last century (Krausmann et al., 2017b). This results in huge challenges for sustainability transformations (Görg et al., 2017).

2.3.5.4 Efficiency potentials in resource use

Figure 2 .24 presents global efficiency cascades and improvement potentials for energy, water, and using steel as an example for materials as well.

Within the context of energy, the final demand and subsequent conversion to useful energy and energy services have long been identified both as the least efficient part of the global energy system and as having the largest improvement potentials. Second, improvements in end-use efficiency leverage significant upstream savings in energy resources. Conversion efficiency from primary to useful energy in the global energy system is currently around 40% (Figure 2.24, panel a). This means that one unit of useful energy conserved through efficiency improvements translates into a reduction of 2.5 units of primary energy. Nakićenović et al. (1990) extended traditional energy efficiency calculations to include energy-service provision. The conversion efficiency of total primary energy inputs into energy services delivered is conservatively estimated at 14% on average for the global energy system in 2020. This means that improving energy efficiency at the service level by one unit yields a reduction in primary resource requirements by a factor of seven.

Lastly, as demonstrated by Riahi et al. (2012), improved end-use efficiency and lower demands also yield significant upstream supply-side benefits, increasing resilience and reliability of supply, and allowing more discretionary choice (failure tolerance) among often contested supply-side options such as nuclear or carbon capture and storage.

A comparable efficiency cascade for water (Figure 2.24, 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%. These losses in water embodied in farm products arise from conversion losses in animal protein production, food losses in food retail and distribution and - above all - in food waste at end-use consumers, estimated to amount up to 30% in industrialized countries by Gustafsson et al. (2011).

The case of steel (Figure 2.24, panel c) also confirms above conclusions: 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).[3]

Any physical loss of resources due to processing, production, or consumption waste not only increases the overall environmental footprint of consumption it also translates into higher costs. Estimates (Ekins et al., 2016) of economic savings across a range of natural resources (energy, water, food, materials) are substantial estimated to total US$3,704 billion by 2030. Around 54% (US$1,511 billion) of the itemized specific savings (US$2,812 billion) accrue at the level of end-users and consumers (Ekins et al., 2016). Improving end use and consumption efficiency under a "responsible consumption" paradigm thus has not just environmental and resource benefits, but also economic ones. These are particularly salient for improving the material wellbeing of the poor where efficiency and waste minimization allow to maximize the social benefits of material wellbeing while minimizing costs and resource use.

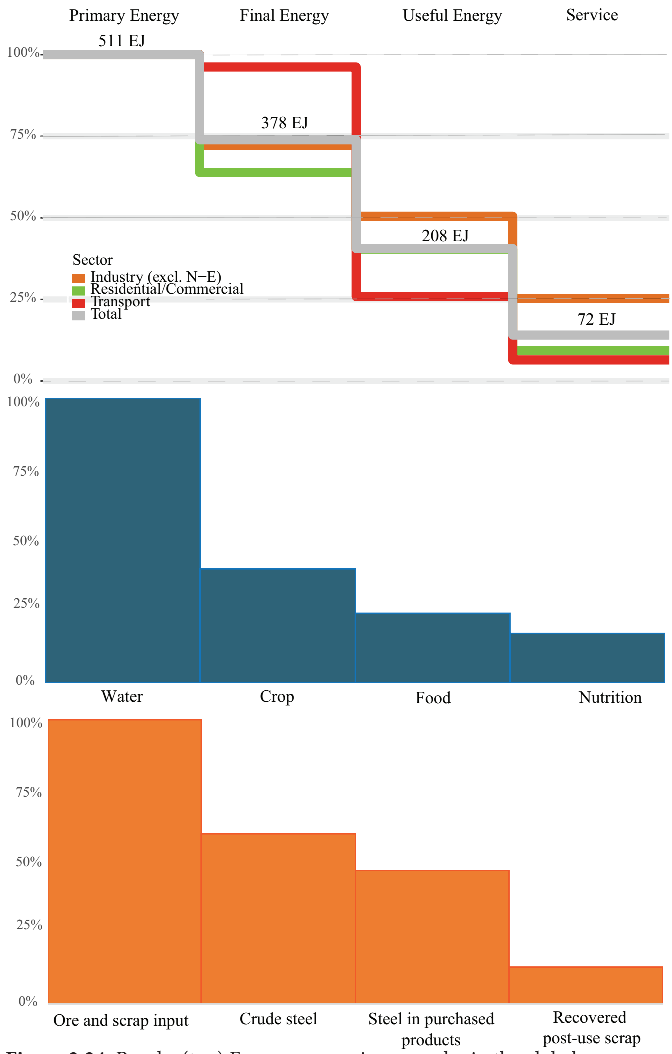

Figure 2.24. Panel a (top) Energy conversion cascades in the global energy system. Lines show percent of extracted primary energy delivered as final energy, useful energy, and services respectively for three end-use sectors (industry, residential & commercial buildings, transport) and totals for the whole energy system in 2020. Energy flows exclude non-energy feedstock uses of energy (labeled as N-E). Total energy flows (EJ) are shown at each stage of the energy conversion cascade. Service efficiencies are first-order (conservative) estimates based on Nakićenović et al. (1990) and Nakićenović et al. (1993). Panel b (middle) Irrigation water embodied in global food: resource efficiency cascade (percent of original irrigation water remaining in respective step of conversion chain). 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 are comprised of additions to the material stock in 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); Fischer-Kowalski et al. (2011); Ayres and Simonis (1994). Figure provided by courtesy of Arnulf Grubler and Benigna Boza-Kiss.

[3] Data for global steel production in 2016, updating (Jonathan Cullen, pers. comm.) Allwood, Cullen et al. (2012).

2.3.6 Decarbonization and energy

After thirty years of increasingly intensive and wide-ranging research and debate, most of us are aware of the fact that since the Industrial Revolution global societies' ability to use fossil energy has been a necessary element in the societal, environmental and material dynamic that has, over the last 250 years, created our modern world. We are completely dependent on using huge quantities of non-human energy. Most of the drivers behind this dependency are well-known: human settlement in not very suitable places such as deserts, the introduction of many creature comforts, and increasing dependency on long-distance transport of basic necessities, to just name a few. Yet this dependency is coming to haunt us, as it is responsible for greenhouse gas emissions and climate change. We urgently and imperatively need to change this dynamic, and a number of ways in which we can attempt to do so are emerging, as discussed in the following sections.

2.3.6.1 Conceiving an optimal energy system

For a general framing of energy consumption at the meta level, the concept of the 'energy triangle' is often used, which classifies the objectives along three dimensions a) economic viability, b) environmental soundness and c) security of energy supply. The transformation of these objectives into metrics at various scales needs to consider context specific circumstances and implies normative judgments.

One of the first energy model-based assessments at the global scale to adopt a normative set of goals was the Global Energy Assessment (GEA) (GEA, 2012). The four goals were to 1) ensure energy access, 2) reduce air pollution and improve human health, 3) avoid dangerous climate change and 4) improve energy security. They represent domains in which the current system is clearly inadequate.

Based on the findings of GEA, work of the International Energy Agency (IEA) on access, work of the International Renewable Energy Agency (IRENA) on renewable energy and other literature the UN Secretary General's High-Level Advisory Group on Energy and Climate Change has identified two complementary domains where progress needs to be made:

- The need to provide universal access to modern energy services;
- The need to reduce global energy intensity by 40%;
- The need to double the share of renewables in final energy to 30% also by 2030, was added later.

The three SDG 7 targets for 2030- provide universal access to affordable, reliable and modern energy services; to increase substantially the share of renewable energy in the global energy mix; and double the global rate of improvement in energy efficiency- closely mirror these earlier goals. In the following section, we will consider the three SDG targets and the targets for climate change mitigation and health to evaluate currents trends in the global energy system.

2.3.6.2 The current situation is inadequate

In the past 15 years an additional 600 million people, mostly situated in Africa and Asia gained access to electricity, lowering the number of people without access to 1.1 billion in 2016 (IEA, 2017). Due to recent cost decreases, electricity access can increasingly be supplied by renewables, in particular by off-grid solar, which however is not sufficient alone for constant access. Despite the progress in many parts of the world, current trends and policies according to the latest IEA (2017) projections will still *leave about 700 million people unserved by 2030, primarily situated in rural areas of sub-Saharan Africa*.

Universal access to clean and modern energy for cooking is currently far from attainment as some three billion people still rely on traditional non-electric energy sources for cooking and heating. While in principle a more rapid scale-up of new technologies is feasible, the current rates of new people gaining access to clean options are far too low. The lack of access to clean fuels and technologies for cooking, and the resulting household air pollution are also cause for some four million deaths from NCDs including heart disease, stroke and cancer, as well as childhood pneumonia (WHO, 2015a).

In the past years the share of renewables in total final energy consumption has been rising gradually to about 20% today, whereby most of the dynamics have taken place in power provision, with water, solar and wind power contributing the most (REN21, 2018), whereas action in the heating and transport sectors is lagging behind. Recent growth rates in the share of renewables in total final energy consumption average around 0.2 percentage points per year (IRENA, 2018).

Energy efficiency improvement at global level, expressed by primary energy intensity, has long been in the order of 1.4% per year and recently has seen some significant reductions, stepping up to about 2% per year. This additional push was mostly achieved by additional efforts in key end-use sectors (buildings and industrial facilities), whereas supply-side potentials remain largely untapped. But even with this increase, advances are insufficient.

The fact that the energy sector currently emits about 32 gigatons of carbon dioxide ($GtCO_2$) per year accounts for about 80% of total global emissions (Le Quéré et al., 2018). In past years, the yearly emission levels have been a race between carbon intensity reductions in the energy mix and increasing energy demand due to economic and population growth. Due to the stronger improvement in carbon intensity reduction caused by progress towards the SDG 7 targets in more recent years, emission levels that have been steadily increasing thus far could at least be stabilized. The IPCC (Pachauri et al., 2014) estimated that from 2011 onwards (at 66% likelihood) the remaining carbon emission would be 400 $GtCO_2$ for staying below 1.5°C and 1,000 $GtCO_2$ for staying below 2°C. From this budget however already about 280 $GtCO_2$ have been used since then (Le Quéré et al., 2018). At current ambition level, i.e., the full implementation of the nationally determined contributions, available global carbon budget for 1.5°C with 50-66% probability will already be well depleted by 2030 and only 20% of the budget for 2°C would be left (UNEP, 2017). Some recent studies (Goodwin et al., 2018; Millar et al., 2018; Tokarska and Gillett, 2018) indicate that the remaining budget could be slightly higher as less of it would have been used in the past. This however does not change the implications that much more transformative actions including a large-scale phase-out of coal are needed.

2.3.6.3 Drivers of energy system transformation and current trends

The decisive driver for all activities along the energy value chain is the demand for energy services, which has changed quite dramatically over the past 150 years or so in terms of magnitude and structure, mainly caused by population and income increases and the fact that new services became available (Grübler et al., 2012). This transition, only made possible through technological innovation both in energy supply and end use, has been characterized by two major transformations. The first of these was the development of the steam engine triggered the substitution by coal of traditional energy sources- which human development had relied upon thus far – a transformation that lasted until the early 1920s, when coal reached its maximal share of close to 50% of global primary energy.

During the second energy transformation, primary energy demand increased even more rapidly, reaching up to 6% growth annually in a period from the late 1940s to the early 1970s. This development phase was characterized by two features. The first was an increasing diversification of both energy supply sources and energy end-use technologies. Perhaps the most important innovations were the introduction of electricity as an energy carrier which could be easily converted to light, heat, or work at the point of end-use, and of the internal combustion engine, which revolutionized individual and collective mobility through the use of cars, buses, and aircraft (Grübler et al., 2012; Nakićenović et al., 1998). The second was a gradual transition towards cleaner grid-bound fuels and energy carriers that has led to a decrease in the specific emissions of CO_2 per unit of energy. The current rate of decarbonization is however far too low to bring the aims of the Paris Agreement within reach and a continuation of past trends is insufficient to bring us on track for the achievement of other energy reductions.

There are however positive signs that give reasons for hope that non-linear change could be possible in the future. Today, we are probably at the brink of another energy revolution, where again technological innovations in combination with regulatory and behavioral changes offer the potential for disruptions in the future evolution of the global energy system. In particular, we want to point to a set of trends here summarized under four headings that are likely to substantially transform the future shape of the energy system and – if managed well – can positively affect the achievement of energy targets and objectives.

2.3.6.4 Technological innovations triggering cost dynamics

While different constraints in the energy system have imposed challenges, they have also frequently triggered new innovation. The development phase of the energy system in most of the last century was characterized by relatively high levels of energy security due to abundant supply with fossil fuels paired with modest environmental constraints so that energy innovation was rather inert. The oil crises in the 1970s raised new awareness for security of supply, and in particular concerns about climate change added new constraints to the way we transform energy. This was the start signal for the search of new, cleaner and more decentralized options to transform energy and has led to a strong uptake of modern renewables in the energy system, in particular in the electricity sector. The market uptake also brought about – facilitated by learning by doing and the modular, granular nature of many renewables – cost decreases that could not have been anticipated some time ago. In particular, the falling cost of solar photovoltaic (PV), which today in auctions has reached levels of some US$40 per Megawatt hour (MWh) below the costs of fossils, has been a tremendous success story. This gives hope that energy system transformation and universal access can be accomplished at faster rates than observed in the past thus far. It will be key to achieve similar successes, both in terms of technology and costs development, for energy storage technologies and options.

2.3.6.5 Energy sector integration and digitalization

Another important trend is that the traditional systems boundaries within the energy system and between the energy sector and other sectors continually diminish. Striking examples are the integration of the electricity sector with the heat and transport sectors and the integration of the energy sector as a whole with the mobility or digital sectors. This integration can bring about several advantages with regards to unlocking flexibility options. One key advantage is the enhanced integration of variable renewable generation which at the same time offers the opportunity to decarbonize the heat and transport sectors through increased electrification. The integration across sectors also goes along with enhanced competition between (formerly) different types of players seeking to provide consumers with energy services and leading to new innovations. For instance, mobility companies develop new energy storage concepts that can also be used in balancing supply and demand in the energy system. Digital companies add 'smartness' that helps make sense in connecting many small units to a functioning system. For instance, lots of decentralized renewables can be bundled into a virtual power plant, demand can react in real time to supply changes or shared cars and bicycles can be allocated in an optimal way and coordinated with other transport options in this manner.

2.3.6.6 Prosumerism and environmental awareness

The two trends in renewable energy expansion and digitalization also provide energy consumers with new opportunities. This, together with increasing interests to be more self-sufficient and autarkic, has led to new conceptions of energy supply where households and other consumers directly supply their own energy needs through distributed technologies (e.g., rooftop solar PV, heat pumps) and even sell their excess generation to the market, or to neighbors connected via a micro-grid, through technologies such as blockchain. Suddenly, energy is not just a commodity anymore, but has become more tangible lifestyle issue, which has caused additional willingness to pay for green innovations. This goes along with an increased notion of energy services rather than merely supply, and in turn creates new incentives to deploy efficiency potentials. While this phenomenon is currently mostly concerned with certain lifestyles in industrialized countries, it has the potential to trigger innovations in these fields that prospectively can be to the benefit of all consumers.

2.3.6.7 Policies at all levels

Growing public concern has propelled policymakers towards action. At the national level a widespread adoption of instruments to support the expansion of renewable energies has taken place. In 2016, 126 countries had corresponding regulations (feed-in tariffs, portfolio standards, etc.,) in place in the power sector and 68 in the transport sector (REN21, 2018). At the international level the nationally determined contributions hold 195 signatory countries of the Paris Agreement accountable to implement measures leading to the achievement of this target. But policies have also been implemented at subnational scales, and in the private sector, often in the form of bottom-up self-commitments. For instance, in the RE100 initiative more than 100 of the world's largest companies committed to 100% renewable electricity. But it will be clear from the earlier parts of this section, that this is far from sufficient to turn the tide.

2.3.7 Food, biosphere, and water

Food security for the world has been a major consideration, and in particular the need to achieve SDGs 1 and 2. It is clear that we will not achieve these goals without major changes in our water management and food production systems, but also global transformations in attitudes towards food, including an important shift towards consumption of plant foods (with the added benefit of reducing diabetes and related afflictions among the overconsuming population). Another dimension of this issue is the reduction of food waste, which in some countries amounts to about 50% of foodstuffs brought into the market.

2.3.7.1 Agricultural land use

Land use for provisions of food, fiber, wood and energy is one of the foundations of our current human civilization (DeFries et al., 2004). There was, and in certain quarters there still is, growing pessimism about the possibilities of feeding growing populations, as exemplified in the writings of Malthus. But contrary to Malthus' predictions, global agricultural production has grown much faster than global population in the past half century, not eliminating hunger and malnutrition but allowing for a dramatic decrease in the proportion of the world's people at the risk of hunger (Rosegrant and Cline, 2003). The food needs of the growing population of currently about 7.6 billion people (UNDESA, 2017) were met by expanding the cultivated agricultural area and by a technological revolution that has increased yields through increases in modern inputs such as irrigation water, improved seeds, fertilizer and pesticides (Tilman et al., 2011; Rudel et al., 2009).

However, land is a limited resource that has to fulfill multiple functions and the gains associated with increased agricultural production have been counterbalanced by harmful impacts on the environment and on ecosystem services. Agricultural land-use activities – whether converting natural landscapes for human agricultural use or changing management practices on human-dominated lands – have transformed a large proportion of the terrestrial surface so that today's agricultural systems (cropland and pasture) occupy about 40% of the Earth's ice-free land surface (Foley et al., 2011). The transition from wild lands to agricultural use over the past several hundred years has for example strongly reduced previously forested lands (Gibbs et al., 2010). Such land-use changes often came along with unintended consequences such as changed freshwater flows and considerable losses of biodiversity through the reduction and modification of habitats (Newbold et al., 2015; Gibson et al., 2011). In recent decades, agricultural intensification, when existing lands are managed in order to be more productive, often through increased use of irrigation and fertilizers, has been responsible for most of the increases in agricultural production. Hence, agricultural freshwater-use for irrigation accounts for around 70% of human water withdrawals (Rost et al., 2008) and plays an important role in global food production.

Due to such disturbances, many freshwater ecosystems have been degraded (Grafton et al., 2013) and as a consequence, freshwater vertebrate populations have declined and many of the world's amphibian species are threatened with extinction (Dudgeon et al., 2006). Furthermore, global nitrogen fertilizer application has increased by 800% and large amounts move into aquatic ecosystems (Galloway et al., 2003), leading to groundwater pollution and increased nitrate levels in drinking water, marine eutrophication, blighted coastal zones as well as increased frequency and severity of algal blooms. Such modern agroecosystems are also often depleted in biodiversity and habitat heterogeneity, with a reduction in resilience as a result of their biological monotony. Both agricultural expansion and intensification are also major contributors to climate change. Agriculture is responsible for a huge share of global greenhouse gas emissions, largely from tropical deforestation, methane emissions from livestock and rice cultivation, and nitrous oxide emissions from livestock and fertilized soils (Smith et al., 2013).

In the future, the land-use systems will be facing new intersecting challenges. The global population will continue to grow and combined with higher purchasing power, especially in developing and emerging countries, food demand will increase and a greater demand for resource-intensive livestock products is to be foreseen (Popp et al., 2017; Bodirsky et al., 2015).

In addition, substantial environmental change – such as increasing temperatures, ozone concentrations, and salinization or decreased water availability could affect agricultural yields, carbon stocks, freshwater resources and biodiversity strongly (Rosenzweig et al., 2014; Schewe et al., 2014). This will be the case for cereal crops that feed the majority of the world's population, but also for vegetables, legumes and fruits – which are important constituents of diets (Scheelbeek et al., 2018). The latter could have further implications for levels of malnutrition beyond caloric intake, such as vitamin and mineral deficiencies. In addition, the faster growth rates associated with higher atmospheric concentrations of carbon dioxide result in lower values of protein, micronutrients, and B vitamins in several important cereal grains (Liu et al., 2016; Loladze, 2014; Myers et al., 2014). Furthermore, biodiversity loss, including of critical crop pollinators, and loss of soil quality will have substantial adverse impacts on global fruit supply and - in turn - on population health (Smith et al., 2015).

On the other hand, to avoid negative impacts of climate change, huge potentials for climate change mitigation for the terrestrial system have been discussed, by providing biomass for bioenergy or conserving carbon rich ecosystems from agricultural expansion (Popp et al., 2014). These additional pressures would pose huge challenges for the sustainability both of food production and of terrestrial and aquatic ecosystems and the services they provide to society.

Therefore, more sustainable land-use methods, less resource-intensive diets but also new incentives and policies for ensuring the sustainability of land use and the protection of ecosystem services are needed in a future world that is even stronger exposed to challenges and pressures (Humpenöder et al., 2018).

2.3.7.2 The role of the oceans and their coasts

The Organisation for Economic Co-operation and Development (OECD, 2016) report on the blue (ocean) economy identified it as "essential to the welfare and prosperity of humankind" and as "a key source of food, energy, minerals, health, leisure and transport upon which hundreds of millions of people depend." The report stated that our "maritime industry landscape is poised to undergo a profound transition" and estimated that economic activity will double to US$3 trillion by 2030.

Concomitant with these developments will be the need for existing and emerging industries to operate in a changing climate, which is already profoundly affecting the rapidly changing and developing world's coastal zones and the livelihoods of coastal people. Coastal societies and economies strongly interact with the ocean. Coastal zones are home to over 10% of the world's population and are experiencing up to three times higher population growth and urbanization rates compared to inland areas (Neumann et al., 2015). Currently, most of the world's megacities are located in coastal zones and many of these megacities are situated in large deltas, where combinations of specific economic, geographic and historical conditions have historically driven coastal migration. Extreme events affecting coastal infrastructure and activities; extraction of groundwater and oil resources leading to accelerated subsidence; the redistribution of commercial, recreational and keystone habitat forming species; increased outbreaks and toxicity of harmful algal blooms; increased habitat destruction and productivity declines through acidification on economic and health impacts are some of the issues that coastal regions will face over the forthcoming decades. These issues constitute barriers to sustainable development of coastal regions.

Embedded within the complex socio-ecological systems that encapsulate coastal communities is the need to adapt to rising sea levels, which will shape coastal areas in the years to come. In this context, sustainable development of coastal regions must balance the trade-offs between the needs of increasing coastal populations for food, energy and shelter and the conservation of biodiversity.

2.3.7.3 Food, materials and energy from the sea

Meeting the food requirements of a growing world population will be one of the major challenges in coming years. The ocean hosts some of the most productive ecosystems and will play a crucial role in the provision of protein and essential nutrients (Beveridge et al., 2013; Kawarazuka and Béné, 2011). Sustainable wild capture fisheries are likely bound below 130 million tons per year, but mariculture production is increasing rapidly (Pauly and Zeller, 2016). Thus, marine food production is to continue making a significant contribution to human prosperity and wellbeing, with small-scale and artisanal fisheries and mariculture production providing not only food but also employment and income for millions of people (FAO, 2016). However, in the face of climate change, pollution, growing competition for natural resources and the changing geopolitical landscape, the sustainable development of ocean food production, both in capture fisheries and aquaculture, is under pressure (Jennings et al., 2016). In addition, continuous overfishing and intensive mariculture currently still exert major pressures on the ocean's ecosystems by depleting fish stocks, degrading habitats, altering native species compositions, and introducing infectious diseases.

At the same time, future requirements for raw materials and energy are steeply increasing and might not be satisfied through conventional sources. The ocean might hold some of the future energy sources through renewable energy production, wind, wave, tidal, in coastal and even off-shore areas. In addition, the deep ocean, with the deep seafloor, is supposed to contain some crucial new sources of minerals, energy and genetic resources. However, answers to how to mine these resources in an environmental least impacting way and how deep-sea mining can be reconciled with the concept of sustainability while contributing to sustainable global development are yet unknown.

2.3.8 Smart cities

2.3.8.1 The dynamics of urbanization

Urbanization is one of the major drivers of societal and environmental change and is a major topic of discussion in the sustainability context (Seto et al., 2017; Seto et al., 2012). It is in effect the most long-standing materially observable societal transformation that we know, as it originated around 6,000 years ago. Current projections of the growth of urbanization seem to indicate that by 2050 68% of the global population will live in cities (UNDESA, 2018). As mentioned in Section 2.2, however, it is not clear that such linear projections are trustworthy, as there are a number of factors (high institutional vulnerability, rising transport costs due to climate change, food security, potential changes in governance structure) that may force the drivers of urbanization in a different direction.

Although there are possibly as many explanations for the existence of towns as there are towns (Jacobs, 1961), one recent approach, proposed by (Bettencourt, 2013; Bettencourt et al., 2007) relates their existence and many of their features to societal information processing. Based on allometric scaling analyses, they argue that there is a direct relationship between innovation and urban scale, expressed by the fact that with urban scale (as expressed in population numbers), innovation activities grow super-linearly while energy use grows sub-linearly. Hence, one could argue that the main driver behind urban growth has, since the emergence of towns, been the need for society to process more and more information by reducing communication and stimulating interaction leading to invention and innovation, while energy has served as a constraint to limit urban growth.

Over the past two centuries, the trend towards urbanization has rapidly accelerated alongside the explosion of innovation enabled by the discovery and harnessing of fossil energy that reduced the energy cost of implementing innovations in society. That has created a number of major stresses for the urban component of the global system dynamics (UNDESA, 2018). Urban systems are costly and highly vulnerable both socially and environmentally. As can be seen in many developing parts of the world, economic inequality, crime, food insecurity, lack of hygiene all abound in urban systems unless very costly social and infrastructural measures are put in place. The growth of urban systems has hugely increased the (energy-costly) worldwide flows of goods, including foodstuffs and water, as well as an increasingly wide range of other products across the world. It has thus exploded the footprint of the global urban population.

The growth of urbanization should also be seen in the perspective of the rural depopulation that is occurring, or has recently occurred, in many parts of the world, uprooting communities, transforming landscapes and industrializing agricultural production methods in developed and developing areas.

One of the fundamental questions of capital importance for sustainability in all domains of human endeavor is therefore whether the current trend towards further urbanization will continue as is assumed by the linear projections of our current "business-as-usual" scenarios? In view of our assumption that the need for increased communication has over the long term been one of the major drivers of urbanization, it will be particularly interesting to see how the changes wrought by the ICT revolution will affect global urbanization.

2.3.8.2 Variation in challenges to urbanization

While in developed and some parts of developing countries the very process of urbanization could possibly be redesigned to support sustainable types of solutions (e.g., compact cities for resource and energy efficiency, or the introduction of new technological solutions including those in the ICT sector), in other instances urbanization could be a barrier to the reduction of poverty and cause a relative scarcity of sustainable kinds of investment, such as for appropriate infrastructure. It is not only the application of new technology that is at stake here, but also the response to various socio-cultural-ecological and governance conditions in orchestrating the needed transformations.

In sub-Saharan Africa about a third of the population lives in rural areas - whereas in the European Union only a quarter are rural dwellers. Sub-Saharan Africa is currently (2018) home for some 1 billion people and with growth rates of 2.6%, the figure will jump to 1.4 billion in 2030, reaching 2.16 billion by 2050. Recent projections by the UNDESA (2018) indicate that by 2050, some 42% and 16% of the population will be living in rural areas in sub-Saharan Africa and Europe, respectively.

Rural-urban migration in sub-Saharan Africa is driven by forces that do not follow the known trends experienced in Europe, the USA and China over the past few decades (Martine, 2012). Unlike in the other continents, where the rural-urban migration was, and is, mainly driven by the Industrial Revolution and the development of manufacturing in urban centers, factors like climate change, population pressure and the digital revolution play a big role in case of sub-Saharan Africa. Not only is population pressure affecting the availability of arable farmland and grazing areas, thereby forcing people to move to cities, it also impacts other social sectors like education and health negatively. With respect to climate change, abnormal weather patterns (i.e., severe floods and droughts) experienced in the past few decades have had negative impacts on agricultural production systems (both crop and livestock), forcing more, particularly young, people to migrate to urban areas.

Thus, urbanization will take different forms, and have different consequences for sustainability in different parts of the world.

2.3.8.3 Multi-level interactions

The issues involved relate different systemic patterns at different levels, such as different environments and different forms of cityscape, the combinatorics of complex regional urban-rural settings, and various global forms of megacity collaboration and competition. The current trend is towards unsustainability. To change that, cities have to transform themselves by developing new visions for, and approaches to, city planning, as well as innovative investment strategies. Urban-rural connections will have to be reshaped both with regard to resource/waste flows and with respect to the combined economics of the labor market, the transport system and the infrastructure investments for larger areas, as well as food, water and energy security.

This will have to take distinct forms at local, subnational regional, and national levels. Already, at the global level, connectivity between the mega- (and other large) cities of the world is emerging with respect to governance, through new types of collaborative schemes initiated by mayors and other authorities. These are exploring best practices, identifying new solutions and growing innovative experiments. Other types of actors, such as different representatives from various industrial sectors and from civil society, are increasingly getting involved in the transformation process at large.

2.3.8.4 Time is short

Strong trends point at a further strengthening of the dominance of current urban economic activities that threaten the long-term sustainability of our current urban systems. However, the combination of rising transport costs, food insecurity, local energy provision and ICT developments that will change the pattern of where one physically works, may soften the stress on cities and in part repopulate rural areas, and will offer opportunities for positive change.

These tendencies that support sustainability-directed forms of urban transformation must, however, deliberately be strengthened in all their diversity, and the pace at which innovations are introduced needs to accelerate in order to face the challenges within the different time horizons involved in the SDG initiative. This requires more deliberate investigation, involves political initiatives, the rapid introduction of experimental facilities, and the development of appropriate methods and investments. Many of the large infrastructure transformations needed will have to be planned now and initiated experimentally as soon as possible. They need to take into account the full range of concerns reflected in the systemic interplay of most of the SDGs.

2.3.8.5 Food production and the greening of urban space

In the current world market, the production of food can be seen as ubiquitous, including production at sites very far from where the food is consumed. This trend towards (expensive) global food transportation is unsustainable. Food security and quality, closeness to local norms and preferences and sanitary control reasons argue for closer linkages between the sites of production and consumption, within subnational regional settings (Elmqvist et al., 2013). This should be encouraged by increasing connectivity between neighboring urban and rural areas, so that they are more strongly woven together in mixed “agglomerations”. Changes in the spatial distribution of labor market considerations in such a “mixed” functional wider space are emerging, supported by increased transportation network connectivity and new possibilities generated by ICT (e.g., to partially work from a distant home base). But for the moment this happens only in small, patchy instances. Climate impact will further change the dynamics of the relation between urban and rural, as will regional renewable energy production, such as bio-based fuel production or wind-generator parks. New ICT control and surveillance capabilities will enhance these possibilities.

“Greening” of urban space, including “vertical” plantations on houses and local urban gardening in underused spaces, is another potentially positive trend. The reasons are manifold: economic and social in relation to the production of food and the related risks, but also the use of local ecosystem services of various sorts and water management options. Different psychological and aesthetic reasons drive a varied group of people of all ages, from youngsters to retired people, toward implementation of such activities. But only major upscaling of such efforts will have a noticeable impact on achieving sustainability.

2.3.8.6 Governance and management concerns

Current forms of management and governance are a major handicap in changing urban systems. In urban planning, generally, changes are only thought about and implemented once the need for them is strongly felt. As our urban systems are undergoing accelerated change, social norms, practices and regulations will be changing more rapidly, which will require rapidly developing novel approaches to management and governance that take the new functional relations among the various urban and rural geographical domains of action into account. Currently emerging teleconnections between large (as well as more limited) urban areas can be seen as one contribution. Such connections can be found here and there within fairly limited regional areas, as well as at more global scales.

2.3.8.7 Conclusions

The strong drive for urbanization is clear. But the ways in which it will take form in different parts of the world are very different, as are the conditions under which one may see the emergence of novel ways to enhance sustainability. This calls for international efforts to encourage approaches to comparing developments under different conditions, and using these experiences in yet other locations, which will increasingly to be of crucial concern.

2.3.9 Digital revolution and technology

Technology as an interface between society and its environment has in recent years developed so rapidly and has led to so many increasingly fundamental changes in our lives that it must be an essential part of our discussions. In particular, the NBIC technologies are in the process of fundamentally changing the world.

The role of technology in the global change process is one of the drivers of our present conundrum. Due to major events in the history of Western societies, among them the development of the Enlightenment (leading to a shift in focus from the past to the future alongside the growth of a rational scientific, albeit reductionist, approach to explaining natural phenomena (Girard, 1990)), and the rapid, fundamental changes brought about by the Industrial Revolution (placing abundant fossil energy at the disposal of societies adapting to technological inventions), followed by the inversion that began changing the balance between society and economy in the 1830s and '50s (Polanyi, 1944), technology came into its own as an engine of change. The potential changes are so vast that summarizing them here is impossible.

But it is relevant to consider two aspects of this development. First of all, the fact that it constitutes its own path-dependent dynamic, related to, but not determined by either societal dynamics or environmental ones. It serves as an interface between these two domains but does not follow the logic of either. Its logic is all its own.

Second, that logic has had a profound impact on the ways our current societies process information. From the very beginning of human societies, artifacts have modified behavior by solving problems, thus serving as tools to alleviate specific kinds of information processing. Early stone tools and arrowheads, for example, reduced the information processing needed in cutting down trees and killing game. Bowls, cups, saucers and plates still serve as tools to facilitate unthinking dealing with liquid and solid nutrients. Cars serve to solve the challenges of transportation, channeling the information processing needed to get from point A to point B. Genetic modification changes the information content of the genes involved and thereby alters the challenges involved in achieving changes in the behavior of living beings that suit our needs.

From that perspective, the information revolution is the culmination of a many- millennia long development that transfers specific aspects of human information processing from the brain to the material environment of our societies. In our opinion, therefore, the role of innovations in information technology is more fundamental than that of other novel technologies. Hence, in Section 2.2, we have devoted considerable attention to the ways in which the ICT revolution is currently changing the playing field for many societal trends, notably accelerating certain developments (disintegration of societal structures; changes in values; concentration of power in a very small circle within societies, etc.).

Here, however, we are considering the wider field of technology development, in many different domains, which has developed at a revolutionary speed. That has brought our societies to a position to be able to conceive and realize just about anything. Although the many changes that this revolution brings offer plenty of opportunities to move towards a more sustainable and equitable society globally, for that to happen a number of current, fundamental challenges need to be dealt with:

- Leveling the playing field between governments, major corporations and society. Currently only major corporations are setting the trend in developing technologies in all cutting-edge domains, and this leads to many challenges in the field of privacy, political control, potential misuse of technology, etc. A more balanced approach is needed.
- Reconsidering the idea of continual progress. This approach has driven Western societies since the 17th century and has led to a kind of ever-accelerating race forward that poses the question whether it should, and could, continue. A more balanced approach may be necessary if we are to achieve some form of sustainable balance between society and its environment, and a more equitable distribution of wellbeing among peoples on Earth.
- Understanding and handling innovation. Up to the present day, innovations are introduced to 'solve' emergent challenges (whether these were known or not), and in the process these solutions create new, unanticipated challenges. This is in its current form an unstoppable feedback/feedforward loop.
- Our societies are essentially able to invent anything, given the time, talent and investment. But some of its impact could be directed in a different way if we were much more precise in our ways of thinking about invention and innovation, and in particular if we systematically focused innovation on domains where the need is clear, considered alternatives and invested in understanding potential unanticipated consequences of our inventions with respect to the SDGs.
- Reinforcing our societies' value spaces. In particular, the ICT revolution, but also developments in biotechnology and genetics are rapidly transforming our common societal values. This contributes to the erosion of common values that can threaten societal coherence. To counter this, in a number of societies that were until recently 'open', political control over the media is put in place. However, in the long term, this is likely to trigger potentially destructive reactions. A balance needs to be sought between diversity and adherence to core values on which institutions can be based.

2.4 Conclusion: designing for change

The main conclusions to be drawn from this chapter can be summarized as follows:

- Our current global society has come close to a tipping point in its long-term evolution. Patterns that have been established many years - in some cases centuries - ago have almost imperceptibly led to a conundrum that has our current societies in its grip. The degradation of the natural environment is but one aspect of this, albeit a very perceptible one. Other dimensions of this evolution, here called 'mega-trends', touch on our international diplomatic order, our democratic form of government, the societal and economic health of our communities, our values, etc.
- These mega-trends are currently accelerating very rapidly as a consequence of the ICT revolution, which is likely to change many aspects of our relationships with space

and time, our experience of the natural and societal realms in which we function as human beings, our social organization, etc. Because we are only at the beginning of this development, it is difficult to get a sense of where how this development will play out, but an important period of relative chaos is certain.

- Our reductionist, fragmented approach to science is partly responsible for the fact that many relationships between these trends have not been observed. In particular, we need to develop a better integrated perspective on the world around us, which strives to be holistic, bridging the many gaps between current disciplines and sectors, including the SDGs. That perspective should focus on *learning from the past, about the present, and for the future!*
- Therefore, rather than focusing on individual SDGs or groups of them, we have chosen to define six transformations where the interaction between the many sectors that define the SDGs plays out. These are 1) Human capacity and demography, 2) Decarbonization and energy, 3) Food, biosphere and water, 4) Smart cities, 5) Production and consumption, and 6) Digital revolution.
- We have then attempted to describe some of the major trends in each of these domains, and to accentuate how current dynamics are driving each of them, to a greater or lesser extent, either away from sustainability or insufficiently closer to that goal to have a hope of achieving it in time.

The particular societal dynamic in which we have been involved, globally, over the last few centuries has, in its extreme form, led to the production-to-waste dynamic that governs many present-day societies. Without tackling the core of that dynamic, sustainability cannot be achieved. Technological or other solutions to specific challenges in particular domains will not suffice. That core is the *societal* dynamic that drives human interactions with the environment. After all, humans define what they consider their environments by selecting aspects of that environment that they become conscious of, and many others which they ignore. On that basis, they define the environmental challenges they perceive, and the "solutions" that they conceive to deal with them. Thus, all issues concerning the environment are dealt with within society itself. There is no direct communication *with* the environment, only (self-referential) communication *within* society *about* the environment (Luhmann, 1989).

Hence, the dominant approach to socio-environmental matters, for historical reasons, has focused on their societal dimensions *from the outside* – from the perspective of the environment. It has thus focused predominantly on the *symptoms* of the current conundrum, rather than its causes, on the relationships humans have had with their environment, rather than on the drivers that have pushed societies into the current particular forms of production-to-waste relationships with the Earth system.

Another core lesson from this chapter is that rather than change course when circumstances (whether social or environmental) force us to do so, we have to anticipate the need for change in all we design or decide. Hence the title of this conclusion: designing for change. The developments that our societies have set in motion with the Industrial Revolution have so accelerated change that we can no longer be content to be re-active to what is going on around us in the global socio-environmental Earth system. Instead, we have to anticipate and be continuously interactive with all other elements of the system we are a part of.

Thus far, we have as human societies mainly related to linear projections from the past and present into the future. This is no longer sufficient: the global system we are part of is fundamentally a complex system with many different nonlinearities which, over time, create tipping points and unanticipated consequences of human decisions and actions. Its complexity exceeds our capacities to understand or deal with it. But we can (and must) do better than we have up to now.

Part of achieving that is developing a high-dimensional holistic perspective that stretches our minds across the interactions that are likely to occur between phenomena and dynamics in specific domains. That perspective should replace society at the core of its concerns, rather than the economy. It also requires much more frequent and in-depth reflexivity on all processes in society, so that course corrections can be implemented. Third, it implies the development of our capacity to understand our relationship with the future, to accept the need for anticipation and long-term planning, and the need for a priori evaluation of potential unintended consequences of our decisions and actions.

To achieve these goals, it seems imperative that we adopt a complex adaptive systems approach to sustainability issues. Looking at societal processes bottom-up, identifying the behavior of individuals and all the different groups and networks that constitute societies will give us a very different perspective on the dynamics driving us in an unsustainable direction, and will thus facilitate designing different trajectories to achieve our goals. The ICT revolution is on the brink of enabling us to so, as the combination of 'Big Data', High-Performance Computing, the Cloud and ML together enable us to move away from the traditional social science approach based on polls of a very limited number of people (a few 1000's or 10,000's out of populations of millions or more) followed by generalizing extrapolation onto whole populations. We will be able to analyze the attitudes and dynamics of each of the individuals in populations of millions directly, as is already to some extent done for major elections on the basis of the thousands of data-points about every individual that have been collected by certain companies. That in turn, using network analytics will enable us to trace the emergence of new ideas, attitudes and interaction networks between very large numbers of individuals.

But we are currently not there yet. Let us, in the next chapters, see what can be done with the tools that we currently have at our disposal!

3 Sustainable Development Pathways

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Key Messages

1. **Reaching the full set of Sustainable Development Goals (SDG) by 2030 and continuing on sustainable pathways thereafter requires transformative change in several areas.** Given the linkages between the various transformations, an integrated approach is needed. Model-based scenarios can be a useful tool to explore the efforts associated with these transformations as well as to assess possible synergies and trade-offs between them.
2. **A wide body of literature exists on how goals connected to the environment-related SDGs can be achieved.** For the SDGs related to human development, quantitative scenarios are less common, but relevant characteristics can be identified. They emphasize responsible consumption and efficient production, global cooperation, and good governance of the energy-water-land nexus, aided by reduced inequalities. Recently, several studies have started taking a more integrative, backcasting approach.
3. **Achieving all SDGs will require substantial further improvements of education and healthcare.** Education and health are instrumental in 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 deal with environmental problems. The ambitions go hand-in-hand with the goal to reduce poverty in all its forms and reduce global inequality.
4. **Consumption and production cut across several of the other transitions, by ensuring an efficient use of resources and providing an ideal entry point for integrated pathway development.** Evidence shows that it is possible to considerably reduce demand for resources by taking a more service-oriented approach. This will allow improvement of the overall efficiency of the systems. Changing consumption patterns contribute to achieving sustainability by keeping the size of the system manageable.
5. **Energy efficiency, increasing the share of renewable energy and carbon capture and storage play a key role in decarbonizing the energy system while providing access to modern energy for all.** Achieving the Paris Agreement is still possible but only if combined with focus on a broader set of SDGs. Constraints set by the SDGs require a rapid phase-out of fossil-based power generation: about 100% of electricity will likely need to be produced with zero and low-carbon technologies in 2050. This can only be achieved with a rapid increase in energy efficiency. At the same time, carbon dioxide-removal strategies need to be implemented.
6. **In 2050, the land-use system will have to produce enough food and biomass to feed about nine billion people, to meet demand for wood, fibers and bioenergy.** To limit the food system's environemntal impacts and to conserve biodiversity, current agriculture area cannot be increased. This requires improving land-use practices, dietary changes toward less meat-intensive diets, and increasing the efficiency of the systems rapidly, reversing the long-term trend of falling yields.
7. **Integrated pathways for cities are characterized by high connectivity and 'smartness'.** Pathways show that by 2050 around two thirds of human population will live in urban areas, calling for new investments in urban infractructures. Smart city design can be a major factor for limiting future resource demand.
8. **Digital technologies support the sustainability transition and cut across all the other transformations.** Further digitalization and automation can both support and be a threat to achieving the SDGs. It is therefore important to implement forward-looking governance structures that allow to mitigate potential trade-offs of the digital revolution.
9. **Mobilizing the necessary financial resources will be critical to achieve the transformation towards the SDGs.** This above all comprises a fundamental change in the investment portfolio across all sectors of the economy, towards sustainable solutions. It will also imply an increase in investments.
10. **Further development of model-based scenarios is a key priority.** A list of research priorities can be identified, including i) increasing the coverage of SDGs and their interactions, ii) a stronger focus on efforts to achieve a set of SDGs simultaneously, iii) a better representation of the underlying geographic and societal heterogeneity and iv) better reflection of the importance of societal change and governance dimensions. This will require a multi-disciplinary approach in which integrated assessment modeling is combined with the contribution of other scientific disciplines.

3.1 Integrated pathways

Reaching the full set of UN Sustainable Development Goals (SDGs) by 2030 and continuing on sustainable pathways thereafter towards the wellbeing of the planet and its people requires transformative change in several areas. An integrated assessment of sustainable development pathways (SDPs) will be needed to better understand the enabling factors and requirements for this change, as well as the synergies and trade-offs between different goals. The nature, extent and timing of this transformation can be explored with integrated pathway modeling, which connects where we want to be in 2030 and beyond with where we are today.

Current trends are not moving towards sustainable development (Chapter 2). Although the 1992 and 2012 Rio Conferences resulted in many activities aimed at sustainable development, historical trends have not been reversed in key areas. In fact, projections of current trends indicate that without new policy initiatives, many of the SDGs will not be achieved by 2030. While in some areas (e.g., related to reducing hunger and poverty) progress is expected in line with trends in the last decades, the expected improvements are projected to be considerably slower than aimed for. For other goals (e.g., climate change, protection of biodiversity) trends even often go in the wrong direction. Chapter 2 also discusses some of the key trends that will possibly shape the future during the coming decades, including population growth and urbanization, but also further development of information technology and digitalization. Handling these "megatrends" well will play a key role in ensuring that sustainable development can be achieved in the coming decades.

There is a significant body of literature that has looked into the question of how future pathways that will achieve one or only a few SDGs may look like. Most of this literature has looked into specific issues, such as the energy sector (IEA, 2017; Riahi et al., 2012) climate change mitigation (Kriegler et al., 2015; Clarke et al., 2014). A much smaller set of scenarios has looked into approaches that aim to achieve a wider set of SDGs, some examples are van Vuuren et al. (2015b) and Parkinson et al. (2018). The literature on individual targets, with those studies looking at multiple targets depicting this even more strongly, clearly shows that a fundamental system transformation will be needed to achieve the SDGs in 2030 and further sustainable development beyond 2050.

Cognizant of the mega-drivers literature, a set of key transformations have been postulated in Chapter 2.

- *Enable and improve human capacities and capabilities.* This transformation ensures the development of human capacity by ensuring full access to secondary education and adequate health care and equal chances for all, while at the same time focusing on eradication of poverty and reducing inequality.
- *Ensuring more sustainable consumption and production patterns.* Key characteristics of the second transformation are: ensuring a more sustainable level of consumption by emphasizing a service perspective, including efficiency improvements, lifestyle changes and circular production modes.
- *Decarbonization of the energy system, while at the same time ensuring access to clean and affordable energy for all.* These goals imply that CO_2 emissions of the energy system are reduced to zero by 2050 by rapid introduction of climate-neutral energy carriers.
- *Eradicating hunger while at the same time preventing further degradation of biodiversity and water resources.* Key characteristics of this transformation include more efficient use of food, redistribution, sustainable agricultural practices, higher yields, careful use of fertilizers and efficient use of water for irrigation.
- *Achieving smart and sustainable urban development patterns.* This will ensure that city infrastructures develop to allow for meaningful urban lives, while staying within planetary boundaries.
- *Managing the digital revolution*. The digital revolution and associated trends to automation and cognitive tasks, increasingly taken over by machines, should be targeted so that they support the transition towards reaching the SDGs.

These transformations are intimately linked. Integrated analysis is needed to look into the possible linkages across these transformations - in particular in order to reduce the risk of trade-offs and increase the possibility of synergies. This is needed in order to achieve the vision of how the world should look like in 2050, as presented in Chapter 1: a world in which the SDGs have been achieved and sustainable development has led to prosperity, peace and partnership for all people, while preserving the integrity of our planet.

In this chapter, we assess the scientific literature on pathways towards achieving several SDGs, on the way to achieving this vision. In the remainder of Section , we highlight implications of the linkages across SDGs by briefly looking into important connections in the existing literature (Section 3.1.1) and discussing pathways which follow a more integrated approach (Section 3.1.2), relevant for the six-transformation processes introduced above. In Section 3.2 we discuss the literature on achieving human development goals. In Section 3.3, we assess existing scenario literature on achievement of a set of selected SDGs, which are under review at the High-level Political Forum (HLPF) 2018: SDGs 6, 7, 11, 12 and 15. This includes more detailed insights into the interlinkages from the perspective of these SDGs (Krey et al., submitted). Finally, in Section 3.4 we discuss research implications.

3.1.1 Linkages across SDGs

Each of the six transformations described above is tied to the achievement of many of the SDGs, highlighting the fact that the SDGs are intricately linked. In fact, approaching the SDGs in the context of a sustainable development pathway based on these underlying transformations provides a holistic view on achieving them together rather than in isolation. Several reports and papers have recently focused on the linkages across different SDGs (Krey et al., submitted; van Soest et al., in review; Nilsson et al., 2017; Liu et al., 2016b). Insights into these linkages are key for successfully achieving the SDGs.

SDGs focusing on human capacity building like education, health and gender equality are fundamental for empowering humans to lead a self-determined and prosperous life (Section 3.2). They not only allow people to find decent work and generate income to sustain themselves, but also enable them to undertake climate change mitigation and deal with environmental problems.

Likewise, recent studies (Grubler et al., 2018; Parkinson et al., 2018; van Vuuren et al., 2018) provide an indication that higher efforts in responsible consumption and production (SDG 12) will lead to many co-benefits with other SDGs without significant trade-offs, providing an indication that responsible consumption and production might be a synergistic entry point for many other SDGs. Reducing resource demand may not only positively affect SDGs related to human needs such as energy, water, and food and environmental SDGs on climate, land, oceans, but also may facilitate achieving several of the SDGs related to human capacity, such as health, and society, such as poverty. Further research is needed to assess the economic impact of reduced demand. Finally, these studies also emphasize the importance of transforming production systems, while taking account the crucial linkages between supply of food, energy, water and other material (the so-called nexus).

For decarbonizing the energy system, assessments show that there are strong relationships with several other SDGs. In many cases, there are rather positive interactions, but there are also negative ones (trade-offs). Positive examples include for instance the reduction of air pollution (SDG 3 and SDG 11) (Portugal-Pereira et al., 2018) and providing energy to support human development (SDG 7). One important trade-off could be between bioenergy (and other land-based mitigation options) and eradicating hunger (SDG 2) and protection biodiversity (SDG 15). Large-scale 2nd generation bioenergy deployment forms a key element of 1.5°C and 2°C transformation pathways (Popp et al., 2017; Schleussner et al., 2016; Rogelj et al., 2015), but clearly its use needs to be planned carefully in order to avoid trade-offs with sustainable food supply and preserving biodiversity. Another trade-off may occur between climate mitigation and universal modern energy access objectives if mitigation efforts increase energy costs for the poor (SDG 7). Also, here, it is possible to limit trade-offs by specific policies (Cameron et al., 2016).

For the transformation of agriculture and land use, there are possible trade-offs between producing sufficient food (SDG 2), preserving terrestrial species and ecosystems (SDG 15), and taking climate action (SDG 13). This comes from the competing uses of land for preserving biodiversity and providing food, feed, and fiber for industrial processes, biofuels and carbon storage (Humpenöder et al., 2018; Popp et al., 2011; Wise et al., 2009). It is possible to avoid these trade-offs via agricultural intensification although this will require the management of possible environmental impacts from increased water use (SDG 6) (Humpenöder et al., 2018; Obersteiner et al., 2016) or the use of fertilizers. Diet changes to less meat-intensive diets and reducing food waste (SDG12) can also mitigate land pressure (SDG 15) and decrease food prices, mitigating hunger (Humpenöder et al., 2018; Obersteiner et al., 2016; Bajželj et al., 2014). This also contributes to climate mitigation through leading to lower CO_2 emissions from land-use change (SDG 13) (Springmann et al., 2016a; Stehfest et al., 2009).

The majority of humanity lives in cities which are responsible for a substantial share of economic activity. Hence synergies and trade-offs related to basic needs and services are relevant for the urban population. Urbanization that is inclusive to, for example, providing electricity and energy services, and that promotes urban mobility via electric public transport (avoiding urban air pollution) will provide synergies between SDGs 3, 7, 11 and 13. The demand for long-lived infrastructure and growing urban population shares calls for sustainable investments in buildings and transport networks.

Nilsson et al. (2016) provided an important step by highlighting the importance of these linkages. More recently, van Soest et al. (in review) systematically discussed the linkages across an even wider set of SDGs as discussed in sustainability literature, but also more specifically in the model-based scenario literature. Clearly, more linkages between the SDGs exist than currently covered by integrated assessment models (IAMs). IAMs are strong in covering important linkages related to the energy-water-land-climate nexus, including climate (SDG 13), energy (SDG 7), food security and land use (SDG 2 and SDG 15), water (SDG 6) and responsible consumption and production (SDG 12). Linkages of these SDGs to the other SDGs are represented more sporadically, e.g., the link to sustainable cities (SDG 11) via reduced air pollution and electrification of buildings and passenger transport. Life in the oceans (SDG 14) can be coupled quantitatively to IAM analysis using climate and marine biosphere models, although this has rarely been done to date. In contrast, the modeling of interlinkages to economic SDGs relating to prosperity (SDG 1 on poverty eradication, SDG 8 on decent work and economic growth, SDG 9 on industry, infrastructure and innovation and SDG 10 on reducing inequality) will require major advances in terms of capturing the effect of the digital revolution and machine learning and representing inequality in the models. Finally, the SDGs on human development (SDGs 3, 4 and 5 on education, health, and gender equality) and peace, governance and partnership (SDGs 16 and 17) enter IAM analysis so far merely as assumptions reflected in model parameter settings and scenario assumptions. Despite the current shortcomings in modeling all SDGs and their interlinkages, a range of interlinkages can already be explored with quantitative scenario analysis.

3.1.2 Key characteristics of sustainable development pathways

There are some studies available that look into global pathways consistent with achieving multiple SDG indicators using IAMs. The studies typically are based on a backcasting approach, focusing on the level of effort and measures required to achieve a set of SDGs. These studies show that there are alternative pathways along which the SDGs could be achieved. The analysis also highlights important co-benefits and trade-offs among the different SDGs. Similar IAM tools need to be enhanced in order to cover a broader range of SDG indicators. We use two of these studies together with the wider scenario literature (Box 3.1) to describe some of the key characteristics of pathways that are successful in achieving multiple SDGs and the possible trade-offs. Figure 3.1 shows a selection of sustainability indicators and their future trajectories for the six transformations from a range of sustainable scenarios. We briefly discuss them below.

3.1.2.1 Human capacity and demography

Improving human capacity to promote wellbeing is at the core of the people and prosperity dimensions of sustainable development. Education and health are especially fundamental for this as they empower humans to take care of themselves and participate in economic and social life (Section 3.2). Therefore, SDPs need to achieve a strong increase in educational attainment and health care access of the global population, leading to increases in life expectancy (Figure 3.1b). In SSP1 (Lutz et al., 2018), for example, the number of people with no or only primary education is reduced to 1.4 billion in the age group 15+ (approximately one fifth of the population) in 2030 and less than 0.8 billion (approximately one tenth of the population) in 2050, compared with around 1.9 billion people today. The SDG target on universal lower secondary education by 2030 is only achieved through the leaving of a cohort of students in SSP1, highlighting the high ambition of this goal (Figure 3.1a). This can only be achieved by also including a dedicated effort to educate adults that did not have access to secondary education during their youth. Increased educational attainment is known to have an impact on accelerating the demographic transition and slowing and eventually reversing population growth. A key mechanism here is the empowerment of women. As a result, population in SSP1 peaks below 8.9 billion around mid-century and returns to current levels by the end of the century. This is markedly lower than in other SSPs with less educational attainment. In fact, in SSP3 population size can increase to over 12 billion people causing - all else being equal - higher pressure on environmental systems and societies.

Education and health are also instrumental in enabling people to find decent work and generate income to sustain themselves and to respond to climate change. However, here, other factors also play a role, such as gender equality and equal access to markets for all population groups, a sophisticated robust economy with sufficient supply of high-skilled labor, well-functioning financial markets, and good governance. If these conditions are met in SSP1, per capita incomes can rise to around US$24,000 per year in 2030 and US$40,000 per year in 2050 compared to around US$16,000/year today (in purchasing power parity (PPP)). This is accompanied by a reduction in poverty levels and a broad reduction of income inequality (Figure 3.1c). The reduction of inequalities may have to be supported by redistributive policies to the extent that educational attainment, health and access to markets will continue to vary between people.

3.1.2.2 Consumption and production

A key element of a transition to responsible consumption and production is the notion that wellbeing does not necessarily rely on the consumption of resources per se, but rather on the *services* and *amenities* these help to provide (Creutzig et al., 2018b) (Section 3.3.1). The key entry point for such a transformation is the demand for services in current systems of resource production and use.

Responsible consumption and production cuts across several of the other transitions, especially related to the resource oriented and society-oriented SDGs, providing an ideal entry point for integrated pathway development. Across a variety of resources (energy, water, food, land, materials, see Figure 3.1d-f) end-use demand is the ultimate driver of current resource systems (Section 2.3.9.2) and associated improvements in efficiency

Box 3.1. Examples of pathways looking into achieving multiple SDGs applying the Shared Socioeconomic Pathways (SSPs).

In Section 3.1.2, we draw upon an important body of literature focusing on future societal and environmental changes are the Shared Socioeconomic Pathways (SSPs) (Riahi et al., 2017). The SSPs are based on five different development routes for societal trends: i.e. sustainable development (SSP1), global fragmentation (SSP3), strong inequality (SSP4), rapid economic growth based on a fossil-fuel intensive energy system (SSP5) and middle of the road developments (SSP2). Each of the SSPs has been elaborated in terms of a storyline and various quantifications using models. These storylines can be combined with different assumptions on climate policy, forming a matrix of socioeconomic developments and the level of climate change (van Vuuren et al., 2015b). The sustainable development scenario (SSP1) combined with stringent climate policy can also be seen as an example of a scenario exploring the route towards a more sustainable world – but it should be noted that the SDGs were not targeted in its development. Further information on the SSPs can be found at: https://tntcat.iiasa.ac.at/SspDb/

In addition, we explicitly focus on two studies that have looked into achieving a wider set of SDGs. These are the Roads from Rio+20 study done by the IMAGE team at PBL (van Vuuren et al., 2015a) and a quantitative representation of multiple SDG indicators into the MESSAGE-GLOBIOM framework at IIASA (Parkinson et al., 2018). Process-based IAM like these provide a consistent global picture of interlinked water-energy-land systems transformation under assumptions surrounding future human development and various climate change. The detailed technological representation of the IAM enables quantitative interpretation of the SDG targets for energy, water and climate as scenario outcomes and provides a tool for estimating the implementation costs.

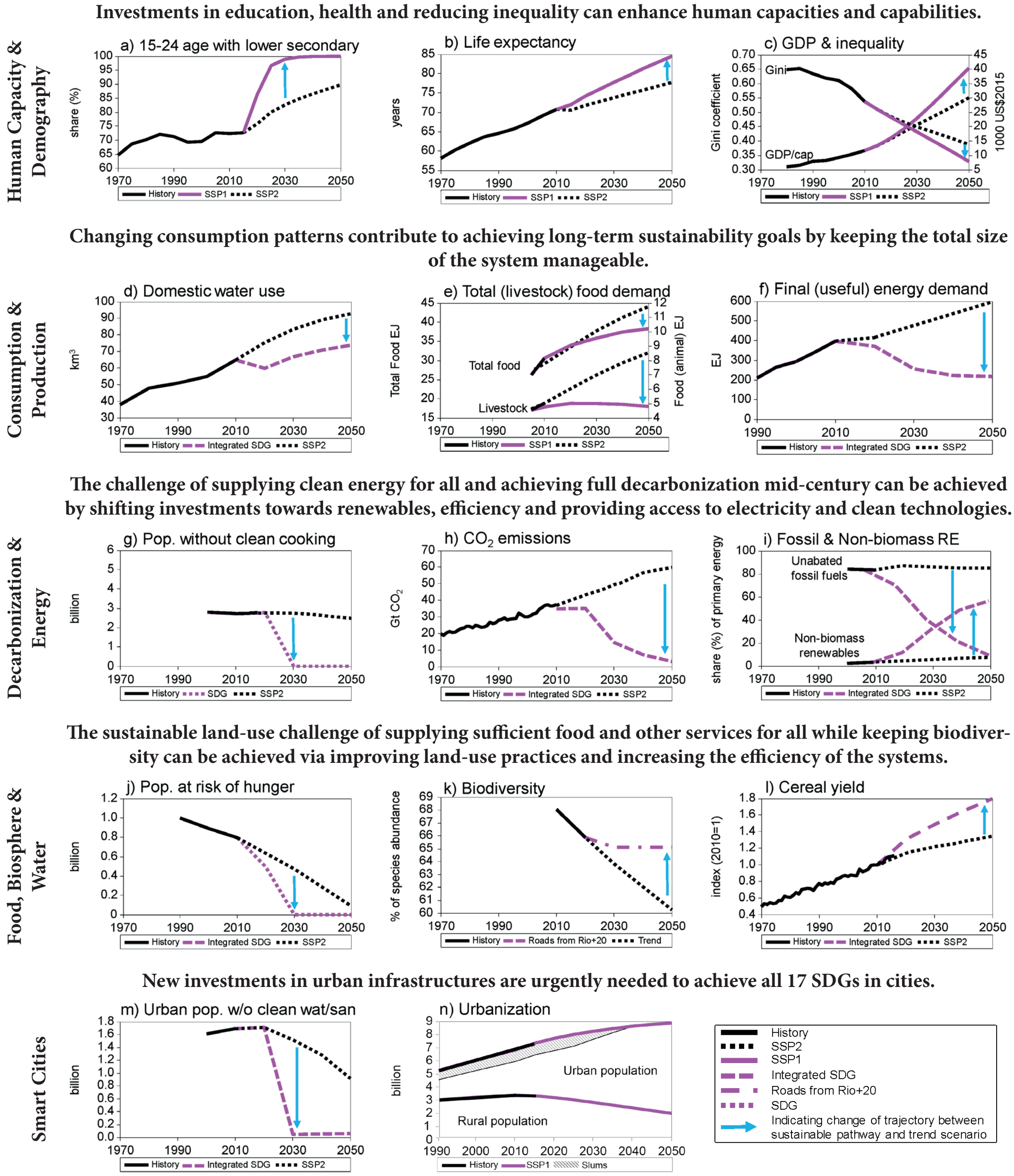


Figure 3.1. Selected sustainable pathways achieving several SDGs and their performance on key indicators, meant as illustration for SDPs. We show select transformation pathways (magenta variants) and a counterfactual trend scenario (mostly SSP2-Middle of the Road, black dotted line) for five of the six transformations till 2050, including recent historic development (depending on data availability). Blue arrows indicate the difference between the transformative and trend scenarios. The transformation pathways are: the "SSP1" (van Vuuren et al., 2017) or the variant looking into stringent mitigation (SSP1-1.9) (solid line), "integrated SDG" from Parkinson et al. (2018) (dashed line), the "Roads from Rio+20" scenario from van Vuuren et al. (2015a) (dash-dot), and scenarios under development ("SDG", dotted) which achieve the SDGs: a) Share (%) of 15-24 year olds completing lower secondary education, b) global average life expectancy at birth in years, c) GDP/capita (1,000 US$2015) and Gini coefficient across countries; d) domestic water demand (km^3), e) total (and livestock) food supply (EJ), f) final (useful) energy demand (EJ), g) population (billion) without access to clean cooking, assuming that the population relying on solid biomass for their cooking energy needs will have increasing access to improved cooked stoves. Note that no baseline scenario currently exists where solid fuels are eradicated as a cooking energy source, h) CO_2 emissions (Gt CO_2) per year, i) share (%) of unabated fossil fuels and non-biomass renewables in primary energy , j) population (billion) at the risk of hunger; k) share (%) of mean species abundance, l) global cereal yield, indexed at 2010; m) urban population (billion) without clean water access and sanitation and n) urban, rural and slum population (billion). The slum population is phased out from 2017 level. Sources: based on data from a) Lutz et al. (2018), b) historic data from UNDESA (2017), Wittgenstein Centre for Demography and Global Human Capital (2015), d), f) h), m) Parkinson et al. (2018), g) historic data from IEA (2017), McCollum et al. (2018b), j) Hasegawa (in preparation), k) van Vuuren et al. (2015a) l) historic data from FAOSTAT (2018), n) Population living in slums from UN Habitat (2016), c), e), l) n) SSP Database (2012-2016).

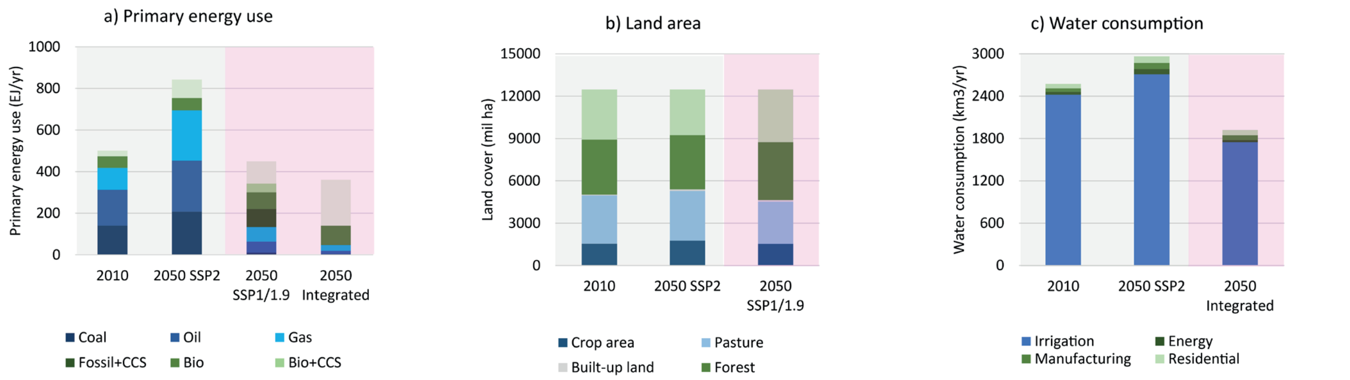


Figure 3.2. Examples of sustainable pathways achieving several SDGs and their performance on key indicators, meant as illustration for Sustainable Development Pathways (SDPs). The figure shows a) primary energy, b) land use and c) water consumption. The transformation pathways are the SSP variant looking into stringent mitigation (SSP1-1.9) from Rogelj et al. (2018) and the "integrated SDG" scenario from Parkinson et al. (2018). SSP data from the SSP Database (2012-2016).

and reductions in wastes therefore offer the largest "upstream" systems leverage effects. A demand or service perspective that emphasizes efficiency increases flexibility on the supply side. Many SDPs are therefore characterized by a very efficient use of energy, food and water, resulting in relatively low demand levels compared to other scenarios. This can be brought about by a rapidly decreasing energy intensity, a strong reduction in food waste and low share of animal products in consumption. The latter is especially important for protecting biodiversity and natural habitat as land can be returned to nature as a result of changes in diets which are less land intensive (Figure 3.1).

Resource use is also the key interface to human wellbeing (as opposed to resource extraction and processing) that is of core concern for a variety of SDGs. Here again, reductions in demand can free resources (natural and financial) for addressing poverty and aiming at a more equitable distribution of material wellbeing.

3.1.2.3 Decarbonization and energy

At the moment, around 1.1 billion people still lack access to electricity and 2.8 billion are not cooking with clean fuels (IEA, 2017; UN, 2017). SDG 7 therefore emphasizes the need to ensuring universal access to affordable, reliable and modern energy services. At the same time, however, the current energy system also forms a key driver of environmental degradation, in particular, climate change and urban air pollution. In this context, it will be important to reduce carbon dioxide (CO_2) emissions from the energy system to nearly zero around mid-century. Scenario studies have looked into the question of how to achieve these targets (Figure 3.1j-i), while at the same time preventing trade-offs with other SDGs.

Several of these scenarios have shown how universal access to energy can be ensured. Achieving this target implies that yearly around 100 million people obtain access to electricity and almost 200 million people start relying on clean fuels and cooking technologies (IEA, 2017). For electricity, this could be based on expansion of both grid-connected and off-grid power supply (in remote areas) (Dagnachew et al., 2018; van Ruijven et al., 2012). Renewable sources would play a major role in such cases, covering up to 84% and 92% of the additional electricity demand in mini-grid and off-grid applications, respectively. For cooking fuels, the SDG implies a shift away in the fuel mix from traditional biomass towards gas (35%), LPG (30%), electricity (17%) and improved biomass (16%) (IEA, 2017). While this will lead to some increase in energy demand, the impact is assessed to be small.

The temperature goals of the Paris Agreement require basically a total decarbonization of the energy system by 2050 (depending on assumptions on the possibility of CO_2 removal) (Figure 3.1i and Figure 3.2a). Constraints set by other SDGs with respect to the sustainable impact on land and water, imply a major role for energy efficiency, electrification and renewable energy. These scenarios require the rapid phase-out of fossil-based power generation: more than 70% of electricity will likely need to be produced with low-carbon technologies in 2030 and about 100% in 2050. The different scenarios also show the portfolio of different options can differ, for instance with respect to the role of wind, photovoltaics (PV), bioenergy and fossil fuel with carbon capture and storage (CCS) (van Vuuren et al., 2015a; Clarke et al., 2014). This allows for some flexibility. The literature also shows that reducing energy demand can play a key role in reducing possible trade-offs (Section 3.1.2.2). While the scenarios also show an important role for bioenergy, either to decarbonize sectors that will also in the future use liquid fuels (e.g., air traffic and some industrial sectors) or to remove CO_2 from the atmosphere (in combination with CCS), its supply is, however, constrained by the need to also meet biodiversity and food SDGs. The Paris Agreement temperature goals require the decarbonization rate to increase from 1-2% historically, to around 4-6% in the 2020-2050 period.

3.1.2.4 Food, biosphere and water

For agriculture, the key challenge is to ensure enough food production to meet the needs of a growing world population and at the same time limit the food system's environmental impacts. This includes, in particular, goals with regard to biodiversity, water scarcity, nutrient cycles and climate change. For biodiversity, it should be noted that historically expansion of agricultural area (at the expense of natural habitats, such as forests) has been the most important factor leading to biodiversity loss (Chaplin-Kramer et al., 2015).

In the period between 2015-2050, global population is expected to grow from seven to about around nine billion people even in more sustainable scenarios (Lutz et al., 2018). Combined with the goal to provide food security and nutritional diets to all people (Figure 3.1j), this could require an increase in agricultural production, in trend scenarios typically in the order of around 60% depending on future diets and a more equal distribution of food supply. Shifts towards less meat-intensive diets in line with health recommendations, reducing food waste and changes in food distribution, could lead to a much lower required increase in food production (see the sustainable consumption transformation). The requirement of protection of biodiversity (Figure 3.1k) implies a reduction of total agricultural land (Figure 3.2b) in order to compensate for the increase in other factors affecting biodiversity, such as climate change. Scenario studies show that this requires stabilization or increases in forest area and significant increases in yields (Figure 3.1l). Historically, about 80% of these increases have been achieved via productivity increases (Smith et al., 2010). Moreover, in many areas yields are still significantly below potential yield levels (Neumann et al., 2010). This means sustainable scenarios are based on a combination of diet change and yield increase. In the most extreme cases, yield improvements would need to return to levels achieved historically. Meeting other SDGs means this transition will have to limit water consumption and prevent a major increase in fertilizer use.

For water, current production practices would entail rapid further growth in water consumption for energy, domestic, industrial and agricultural water use. However, it is possible to reduce water consumption through technological efficiency increases (Figure 3.2c). Water intensity can also achieve a further 30% reduction relative to the baseline demands through assumed improvements in behavior. Technological diffusion constraints related to financial barriers are relaxed to reflect increased access to project financing during implementation of the SDGs. This implementation is described in Parkinson et al. (2018). While these measures can reduce water scarcity, still there will be people living in areas suffering water scarcity. This will require sufficient adaptation measures as well as changes in the governance structures related to water. A deeper dive on nexus governance issues and potential solutions related to the water-energy-land nexus at different governance levels is provided in Section 4.3.

3.1.2.5 Smart cities

Scenarios show that by 2030 around 60% and by 2050 around 70% of human population will live in urban areas (Figure 3.1). Increased economic opportunities and cultural offerings are among the drivers of this trend. Integrated pathways are characterized by high connectivity and 'smartness' of cities. The digital revolution and the availability of autonomous, high-speed transport options however change the nature of urbanization with more people able to connect to the dynamism and services offered by cities in more remote locations, leading to increased integration of the urban hinterland. The rapid urbanization process, however, also poses challenges.

The emergence of polycentric, urban-rural landscapes in conjunction with the digital revolution facilitates the rapid uptake of more localized technologies and production processes such as building integrated PV, smart home systems, urban farming or advanced on-site printing of things, such that cities overall are becoming more self-sufficient, less polluting, and circular in terms of resource consumption. Further characteristics that define cities in the integrated pathway are inclusiveness, access to open spaces (including green areas) and a high level of social interaction. This is achieved, among others means, through a paradigm shift in housing policies that do not any longer lead to segregation by class or race and where housing is no longer considered a purely private shelter but is an essential component of a larger social system giving people better opportunities to connect with each other thus reducing 'urban anonymity'.

As parts of these improvements take place gradually, informal settlements are transformed organically to reach adequate standards. A striking indicator reflecting this progress is the share of people who have access to an improved water source. It reaches 100% in 2030 (Figure 3.1m), depicting the progress towards minimum adequate housing standards and inclusiveness. Slums are eradicated (Figure 3.1n). Paramount to all pathway elements is the capacity of urban city planners to design policies which respect the rights of all city dwellers and enable basic drivers of human wellbeing such as security, trust, local identities, and lively neighborhoods.

3.1.2.6 Digital revolution

Digital technologies support the sustainability transition and cut across all the other transformations. They are both indicators used for tracking the SDGs in themselves (e.g., Internet or mobile coverage) as well as enabling technologies to harness efficiency gains and inducing life style changes, for example in the energy system (e.g., smart metering, car sharing), related to environmental quality and health (e.g., water or air pollution monitoring).

The digital revolution and increased automation of cognitive tasks are expected to be major drivers of change concerning human capacity and prosperity. Digitalization and automation will boost technological progress and provide the next wave of innovation to drive economic productivity (SDG 9), counteracting the risk of secular stagnation. They are also projected to offer large benefits for improving preventive and curative health care (SDG 3) and providing high-quality education (SDG 4). However, if unmanaged, the digital revolution could also lead to a rapid increase in energy consumption. Moreover, they can also have significant impacts on the work force and personal incomes due to rapidly increasing automation. If the increased profits generated by automation accrue to only a few, and if no decent substitutes for replaced jobs can be found, major challengers for achieving SDGs 8 and 10 can occur. Education can again play a large role here for providing people with the necessary skills to adapt to a rapidly changing labor market which may be characterized by an increased focus on human and social interactions and the contextualization of knowledge.

In summary, digitalization and automation can be key drivers and enablers of sustainability outcomes across the SDGs, supported by major investments in research and development. Yet, they need to be managed well (Section 4.4.3) to harness their full potential for the sustainability transformation and avoid adverse impacts. Current models fall short of capturing such disruptive technological advances.

3.1.2.7 Investment needs for the sustainability transition

Mobilizing the necessary financial resources (Figure 3.3) will be critical to achieving the transformation towards the SDGs. This needs to comprise a fundamental change in the investment portfolio across all sectors of the economy. Additional investment needs, estimated in one study to be around $1.4 trillion per year until 2030, can be identified in particular for education (SDG 4), health (SDG 3), sustainable agriculture (SDGs 2, 13, 15), infrastructure (SDG 9) and access to clean energy (SDGs 7 and 13) and water (SDG 6) (Schmidt-Traub, 2015). A large part of financing the sustainable development transformation is not concerned with raising additional sources of investment, but with re-directing existing investments from unsustainable to sustainable activities, such as re-directing investments into energy supply from fossil fuels to low-carbon energy sources.

IAM-based analyses have focused so far mostly on investments needs for decarbonizing energy use and providing energy access (McCollum et al., 2018b; McCollum et al., 2013). These studies have shown that even without new policies investments in the energy system would be around US$2000 billion per year. In addition to a massive shift away from fossil fuels, an additional investment of around US$300-500 billion per year in the period until 2030 (around 17-25% of 2015 energy system investments worldwide) would be needed for decarbonization. Moreover, around US$60-200 billion per year would be needed additionally for providing access to energy. This means low-carbon supply investments will need to overtake fossil investments already around 2025, and reach, in many pathways, an 80% threshold already by 2035. A fundamentally restructured energy system would on the other hand also bring economic benefits, such as for air pollution control costs which would drop close to US$200 billion per year (due to the reduced use of fossil fuels and the need for accompanying pollution control equipment). Consequently, investments into unabated fossil infrastructure (i.e., without CCS) also have to be scaled down rapidly, leading to disinvestments in the order of hundreds of billions of US$ per year by 2050 (compared to baseline pathways without sustainability policies). Investments in energy efficiency and demand-side solutions lead to energy savings consistent with the SDG 12 sustainable consumption narrative, provides significant wiggle room in the form of avoided investment in traditional supply technologies (on the order of hundreds of billions of dollars).

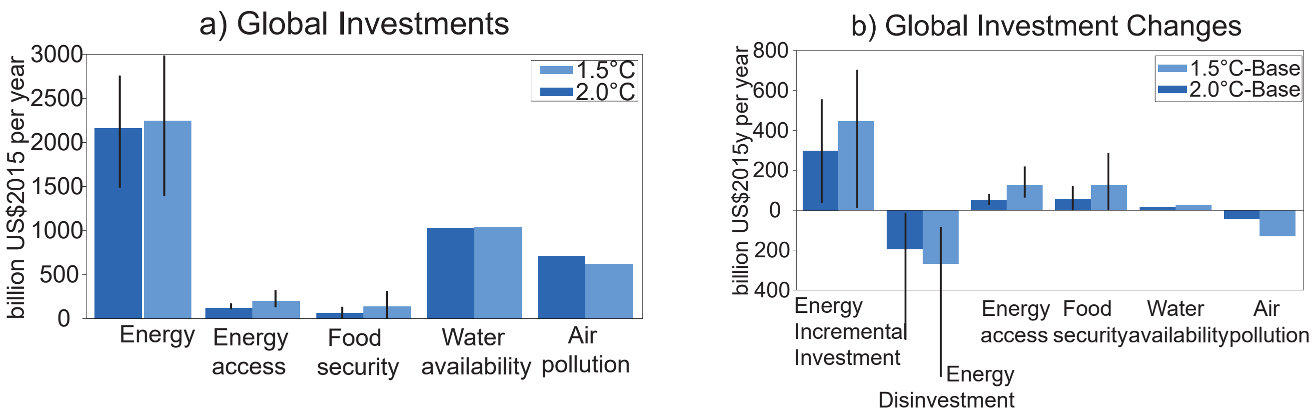


Figure 3.3. Integrated policy design needed to steer sustainable investments towards achieving the SDGs. Projected energy investments for climate mitigation (SDG13) and how they relate to four other SDG dimensions (energy access-SDG 7, food security-SDG 2, water-SDG 6 and air quality- SDG 3). Total (panel a) and incremental change compared to the baseline (panel b) in average annual investments between 2016 and 2030. Light blue bars show mean investment in 1.5°C pathways across results from six different models, and dark blue for 2°C pathways, respectively. Whiskers represent minima/maxima across estimates from six models. Water and air investments are available only for one model. Negative investments reflect reduced investment needs (disinvestments) into fossil fuel (energy sector) or cost savings for air pollution control (synergies). Investments for different sustainable development dimensions denote the investment needs for complementary measures to avoid trade-offs (negative impacts) of mitigation. For example, energy access reflects policy costs for ensuring 100% clean fuel adoption throughout the world by 2030, via subsidies and microfinance for cooking stoves and fuel price support (SDG target 7.1), even in spite of rising energy prices due to stringent climate mitigation. Food security reflects mitigating trade-offs of SDG 7 and SDG 13 policies on the situation of people at the risk of hunger due to potentially increasing food prices, the costs do not correspond to completely eradicating hunger (SDG target 2.1). Water includes achieving SDG targets 6.1 to 6.4 and a wide range of municipal water technologies, excl. irrigation costs. Air pollution represents costs to substantially reduce premature deaths from air pollution (SDG target 3.9). All investment values are undiscounted and in US$2015 per year. Source: estimates from CD-LINKS scenarios summarized by McCollum et al. (2018b).

Investments in the water sector, including pumping, distribution, storage, treatment and conservation will need to be scaled up rapidly to about US$1.2 trillion per year globally in order to achieve the core objectives of SDG 6 (Parkinson et al., 2018). In the water sector, most of the investment is needed in order to develop, maintain and replace piped water and wastewater collection infrastructure, particularly in developing regions currently lacking infrastructure (e.g., South Asia, Latin America and sub-Saharan Africa). Roughly 40% of the investments are needed for the water supply infrastructure; 40% for wastewater collection and treatment; and about 20% of the investments are needed for improving the efficiency of water uses across the sectors. The SDG 6 targets would be partially achieved by accelerated investments into wastewater treatment and wastewater recycling infrastructure. The latter would be used increasingly to support water efficiency targets and demand growth in water-stressed regions. Efficiency investments are an important part of the SDG 6 solution portfolio, leading to reductions in withdrawals and return flows. In the long term, more sustainable consumption and production behavior consistent with the SDG 12 targets provide the foundation for reduced water supply costs when compared to the other scenarios featuring a continuation of current consumption trends.

Infrastructure investments in the energy and water sectors need to be complemented by dedicated measures to improve distributional effects of some of these policies and to assure access to basic living standards for all. This comprises, for example, investment needs in the order of US$225 billion per year to 2030 into universal access to affordable and reliable (cooking) energy, or around US$40 billion per year into food security to assure access to affordable food (in case of land-use changes brought about by with stringent climate policies) and US$180 billion for universal education ((McCollum et al., 2018a), Figure 3.3).

3.2 Transforming human capacity: Health, education and demography

People are at the core of the transformation towards sustainable development and a low carbon society. Not only do human activities drive global environmental change, human beings are also affected by it and thus, long-term human thriving is the goal of sustainable development. In what direction a society will develop and transform thus depends on human capabilities which encompass a set of knowledge, skills, competencies and psychological and physical abilities. In particular, health and education are fundamental elements of human capacities and subsequently the development process. While in the 2030 Agenda health and education are often seen as an outcome of successful development, we argue that they are both means to achieving key sectors of the global development agenda (Bengtsson et al., 2018; Nunes et al., 2016). Poverty reduction, attaining quality education and reducing inequalities, for instance, cannot simply be achieved if a population does not have good health and wellbeing. Likewise, also quality education is a precondition for achieving many aspects of sustainable development (Bengtsson et al., 2018).

In the following section , the transformation of human capacity, with a focus on education and health and its nexus with other SDGs is considered in relation to the 'five Ps' – people, planet, prosperity, peace, and partnership. These five critical dimensions capture the broad scope of the 2030 Agenda adopted by the United Nations.

3.2.1 Education and demography

Education is a key factor for the achievement of sustainable development. First, education has an intrinsic value. For instance, a person may value knowing something since knowledge is intrinsically satisfying. Second, education has several instrumental roles both at the personal and collective levels in promoting productivity and bringing about social change (Drèze and Sen, 2002). Education is a means to exercise all other SDGs because education not only enhances human capital (individual's productive ability) but also human capabilities (capability to achieve valued functionings) (Sen, 1997). Education thus can also have an indirect role in bringing about social development. For example, expanding girls' education can help reduce gender inequality and fertility rates. Figure 3.4 illustrates the impact of education on demography using the SSP1 and SSP3 scenarios (Lutz et al., 2018). The SSP1 assumes accelerated educational and health investments, including successful implementation of SDG target 4.1 on universal secondary education. This promotes the demographic transition, leading to a relatively low world population with increased well–being and a peak in global population in 2050 and a well-educated global population. This strongly contrasts with the SSP3 scenario with much less emphasis on education. The consequence is a much higher, and growing global population at the turn of the century. Moreover, large segments of the population (in less developed countries) have low levels of educational attainment. The low population developments in SSP1 will facilitate sustainable development in several dimensions, e.g., access to clean energy and water and the provision of nutritious diets without endangering biodiversity. All of these would prove major challenges in SSP3.

Beyond its impact on demography, education is a key driver of economic and societal development. While a positive relationship between education and other dimensions of sustainable development has been documented (Baker, 2014; 2007), extant literature on interactions between SDGs still overlooks education as a potential driver of the attainment of other goals (Pradhan et al., 2017; Nilsson et al., 2016). This is possibly due the lack of evidence and knowledge on the pathways by which education influences other sectors of development. Indeed, the benefit of education goes beyond its instrumental value, described in the neo-classical utilitarian economic theory as a tool to acquire skills and knowledge enabling individuals to be more productive and earn higher wages (Becker, 1962; Schultz, 1961). The rights-based discourse perceives education as a fundamental human right. Based on the concept of rights, Amartya Sen (1999; 1985) developed the capability approach which focuses on improving individuals' substantive freedoms or real opportunities to promote or achieve functionings they value and have good reasons to value. Basic education is

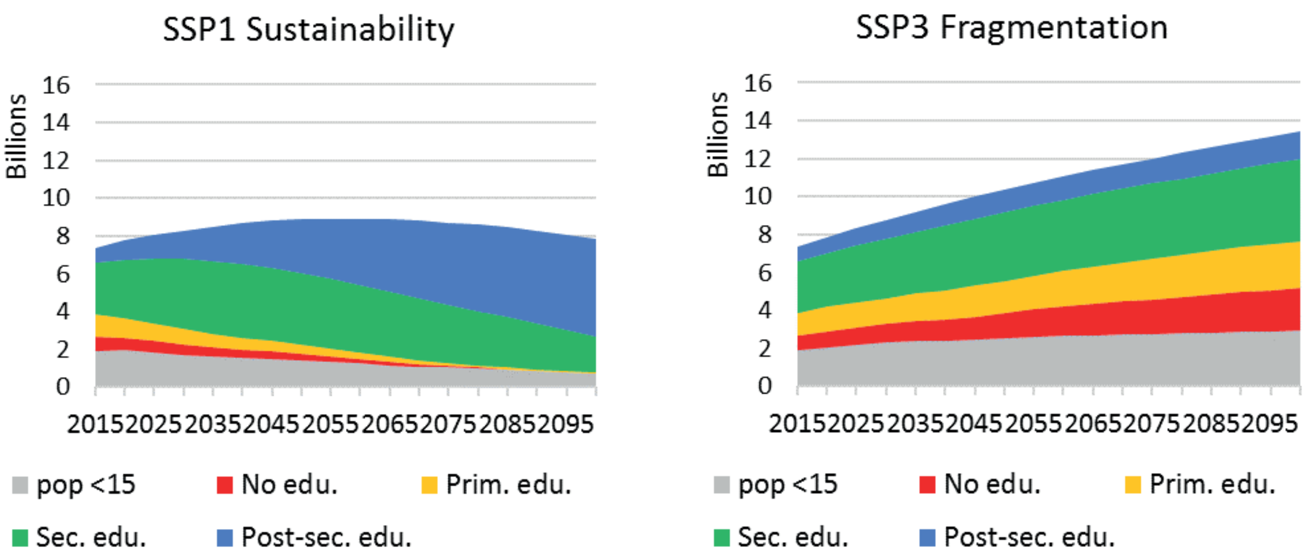


Figure 3.4. World population until 2100 according to two scenarios and educational attainment. Source: Lutz et al. (2018).

perceived as fundamental precondition for developing such capability as well as included as a capability in its own right. In this view, education is also a tool for human empowerment.

Recently, there has been an attempt to conduct a comprehensive review of literature from a wide range of disciplines showing the role of education and learning in driving positive change in environmental and sustainable development and overall human wellbeing. This review is part of the Global Education Monitoring Report 2016 (UNESCO, 2016). The role of education in sustainable development is considered in an integrated manner: by not only linking education with other goals but also looking at reciprocal linkages between them.

3.2.1.1 People

There is abundant scientific evidence on the role of education in promoting human and social development in relation to health, nutrition and access to water and sanitation. This includes health behaviors ranging from smoking, drug abuse mental health, chronic diseases to mortality (Smith and Sagar, 2014; Meng and D'Arcy, 2012; Baker et al., 2011; Cutler and Lleras-Muney, 2010; Cutler and Lleras-Muney, 2008; Grossman and Kaestner, 1997). Children of better-educated mothers or households are less likely to be undernourished (Alderman and Headey, 2017; Pamuk et al., 2011) and have better access to quality water and sanitation (Munamati et al., 2016; Tiwari and Nayak, 2013). By building health literacy and enabling individuals to pursue nutrition and healthy behaviors, education plays a fundamental role in driving people's wellbeing.

3.2.1.2 Planet

While the relationship between education and health is relatively well researched, the link between education and the environment has more recently developed into a research area (Bengtsson et al., 2018). Still education attainment is highly relevant for climate mitigation and adaptation (Lutz and Muttarak, 2017). Education contributes to the reduction of vulnerability to environmental change (Butz et al., 2014; Lutz et al., 2014). For instance, it is found that highly educated societies or households have higher disaster-preparedness, suffer lower loss and damage and recover faster from catastrophic shocks (Muttarak and Lutz, 2014). The relationship between education and sustainable lifestyle and consumption is more complex. On the one hand, highly educated individuals express greater concern about the environment and climate change and are more likely to report carrying out pro-environmental behaviors (Chankrajang and Muttarak, 2017; Meyer, 2015; Muttarak and Chankrajang, 2015). On the other, higher income at the aggregate level education is also associated with greater environmental stress and GHG emissions (Hill and Magnani, 2002; Gangadharan and Valenzuela, 2001). Some scholars argue that the relationship between economic development and environmental degradation will follow an 'inverse-U' shaped pattern whereby at high-income levels, the relationship between income and environmental degradation and pollution reverses, leading to environmental improvement (Stern et al., 1996; Grossman and Krueger, 1991). Education could play a role here in increasing consumption efficiency and facilitating the adoption of modern, cleaner energy sources (Song et al., 2015; Pachauri et al., 2012). The empirical evidence on this issue remains inconclusive (Hervieux and Mahieu, 2014; Goldman, 2012; Carson, 2010). A direct co-benefit of increased adoption of clean energy is the reduction of exposure to indoor air pollution, thus improving the health, especially of women and children (Section 3.2.2).

3.2.1.3 Prosperity

Poverty reduction and economic growth are necessary for achieving shared global prosperity. By raising individual and national capabilities, particularly skills and productive knowledge, education plays a key role in poverty reduction. Likewise, recent studies have consistently shown the positive relationship between education and economic growth, especially by disaggregating the level of educational attainment and age (Crespo Cuaresma et al., 2014; Lutz et al., 2008) and the quality of education (Hanushek and Woessmann, 2008; Hanushek and Kimko, 2000). Given that the SDG agenda explicitly aims to ensure inclusion and equity, it is also important to consider the relationship between economic and educational inequalities. In fact, there is evidence that educational equality in a country promotes income growth (Vinod et al., 2001) and reduces income inequality (Coady and Dizioli, 2018). As the country develops, however, the positive impact of educational expansion on income diminishes. Subsequently, policies that address educational quality are considered to be crucial in enhancing the role of education in reducing income inequality (Coady and Dizioli, 2018).

3.2.1.4 Peace

The explicit inclusion of 'Peace' in the SDG agenda highlights that peaceful and inclusive societies are fundamental for sustainable development. The absence of violence is a prerequisite for peace (Galtung, 1969) and violence and conflict are less likely in societies where institutions are democratic (Hegre, 2014). Likewise, political participation and inclusion are vital to social cohesion and for ensuring democratic transformation. Not only does education increase political knowledge, it also promotes civic culture and participation in democratic politics as demonstrated in the association between education and democracy (Glaeser et al., 2007; Barro, 1999). There is also evidence that education is a more important underlying driver of democratization than income (Lutz et al., 2010). While political participation is higher among highly educated individuals (Mayer, 2011), they are more likely to engage in nonviolent civil actions. Accordingly, it is found that countries with higher levels of primary and secondary school enrolment experience lower risk of outbreak of civil war and armed conflict (Barakat and Urdal, 2009; Thyne, 2006; Collier and Hoeffler, 2004). By reducing deprivation and vulnerability, education thus is a powerful instrument to reduce grievances (Aoki et al., 2002).

3.2.2 Health

As is the case for education, human health is central to sustainable development and improving population health will support achievement of the SDGs. In return, the achievement of each of the SDGs will contribute toward improving health outcomes, either directly, through improving access to and quality of health services, or indirectly, through protecting biodiversity and reducing unsustainable practices that contribute to adverse health outcomes.

3.2.2.1 People

Lack of access to water, sanitation, and hygiene services exposes individuals to diarrheal diseases, which can cause severe illness and death, particularly in infants and children. Estimates based on 2012 data find that lack of access to these services resulted in 842,000 premature deaths from diarrheal disease, over 40% of which occurred in children under age 5 (Prüss-Ustün et al., 2014). Traditional cooking technologies, such as using open fires with biomass or charcoal, result in a heavy risk of respiratory and cardiovascular diseases due to the indoor air pollution these fuels generate, which disproportionally affects women and children. Estimates from 2010 found 3.9 million premature deaths worldwide that year due to household air pollution (Smith et al., 2014). Addressing these challenges requires increased investment in providing safe, convenient, and affordable alternatives to traditional methods for accessing water or energy. Critically, these solutions must be culturally appropriate and address the users' needs. Researching and funding a variety of solutions that address locally-specific needs will be critical to addressing gaps in water and energy access.

3.2.2.2 Planet

Many of the SDGs are targeted at reducing unsustainable behaviors and protecting biodiversity; and doing so would likely positively affect human health. For instance, globally, pollution has immense consequences for global public health. Recent estimates suggest that worldwide, roughly nine million premature deaths are attributable to diseases caused by pollution (air, water, chemical, etc.), with disproportionately high effects on populations in sub-Saharan Africa and South Asia (Landrigan et al., 2018). Fossil fuel use also drives climate change, which is associated with a variety of adverse health outcomes, including from exposure to extreme temperatures, growing ranges of infectious or vector-borne diseases, and more powerful disasters that can lead to injuries or loss of life (McMichael, 2013). Additionally, as CO2 levels rise, nutrient losses in staple crops such as wheat and rice are occurring, leading to vitamin and micronutrient deficiencies (Zhu et al., 2018).

Preventing biodiversity loss also has important health implications for human health, particularly through impacts on nutrition. For instance, fish catches worldwide are expected to fall sharply in the coming decades due to increased fishing pressures and environmental change, placing over 800 million people at risk of micronutrient deficiency (Golden et al., 2016). Aside from the health impacts of climate change, high levels of red meat consumption, as found in many developed countries and increasingly in rapidly developing countries such as China, can result in an increased risk of premature death (Pan et al., 2012). FAO (2011) estimates that 20-30% of food worldwide is currently wasted. Reducing losses across the food system help reduce problems associated with the undernutrition and malnutrition associated with global change (Alexander et al., 2017).

Importantly, policies that reduce GHG emissions can have positive impacts on human health, generally referred to as co-benefits. For instance, reducing emissions from power plants can also reduce other air pollutants, such as particulate matter, that can cause or aggravate respiratory illnesses and cause premature mortality (Chang et al., 2017). Designing urban spaces that encourage the use of active forms of transport, such as walking or bicycling, can reduce the use of polluting vehicles, while simultaneously providing health improvements through exercise.

3.2.2.3 Prosperity

Collectively, the lack of prosperity for all individuals due to poverty and inequality represents one of the most prominent barriers to improving global health outcomes. Recent national surveys from sub-Saharan Africa show that inequality correlates closely with poor health outcomes, knowledge about health, and an inability to receive high-quality health services. For instance, in Tanzania, the poorest fifth of children are at least eight times more likely to test positive for malaria compared to the wealthiest fifth (Ministry of Health and ICF, 2016). Examples such as this illustrate how by shaping individual knowledge and capabilities as well as influencing where and how people live, poverty and inequality can generate health disparities.

Addressing health disparities associated with poverty requires improving access to and the quality of health care services, particularly in the lowest resource settings. At least half of the world's population cannot obtain essential health services, with the result that large numbers of households are pushed into poverty because they must pay for health care out of their own pockets. Approximately 800 million people spend at least 10% of their household budgets on health expenses for themselves or a sick family member (WHO and World Bank, 2017). Policies that promote universal access (SDG target 3.8), such as removing user fees to access public health care facilities, as has been done in countries such as Uganda, can significantly increase service use among the poorest populations (Nabyonga Orem et al., 2011). However, barriers such as inadequate finances and low levels of human capital hinder universal access goals in low- and middle-income countries (Frenk, 2015).

3.2.2.4 Peace

SDG target 16.1 seeks to reduce all forms of violence, which takes a considerable toll on global public health. Estimates show roughly 150,000 deaths worldwide in 2016 due to acts of war and terrorism, with an additional 390,000 deaths due to interpersonal violence (Naghavi et al. 2017). Globally, women and girls are more likely than men and boys to experience intimate partner violence (Desmarais et al., 2012). SDG target 5.2 calls for eliminating all forms of violence against women and girls, yet there is a long way to go before this target is met. Global estimates for experiences of intimate partner violence are troublingly high—over 40% of women age 15 or over in sub-Saharan Africa and South Asia have experienced intimate partner violence or sexual violence from a non-partner at some point during their lifetime (World Health Organization 2013). Even in high-income countries, roughly one in three women have experienced such violence. Children are also disproportionately harmed by violence, the effects of which can stretch well into adulthood due to an increased risk of mental health disorders (Norman et al., 2012). SDG target 16.2 articulates the need to eliminate all forms of violence against children. Achieving SDGs related to health and violence will require a range of efforts to address violent conflict, as well as the causes of interpersonal violence. Reducing gender-based violence requires developing, testing, and scaling interventions to prevent violence, particularly in low- and middle-income countries, as well as changing legal regimes that place women at greater risk of violence. Globally, there is a lack of evidence on interventions designed to prevent gender-based violence, and most of the outstanding evidence is from high-income countries, despite a greater risk of violence in low- and middle-income countries (Ellsberg et al., 2015). Moreover, programs which support caregivers when children are young can help reduce the risk of violence against children (UNICEF, 2014). Recent estimates suggest that among the nearly two billion children age 2-17 around the world, at least half (54%) experienced some form of violence during the past year, rising to over three quarters (76%) when moderate forms of violence such as spanking are included (Hillis et al., 2016). In jurisdictions without specific penalties for domestic violence, creating such penalties can help discourage potential perpetrators and hold abusers accountable for their actions.

3.2.3 Investments in health and education

The two-directional positive link between health and education indicates that there is a self-reinforcing positive feedback: educational improvements cause health improvements, which in turn affects education positively. Such relationships are very powerful in providing an (in this case) desirable change (Collste et al., 2017). However, there are also fundamental delays in the feedbacks between the two and how they affect development overall. As only children go to school, it takes time for the full effects of educational investments to have an effect on a societal scale and impact e.g., fertility outcomes and labor force productivity. Educational achievements are also dependent on the development of other sectors. For example, investments in infrastructure in rural areas (SDG 9) promotes access to schools and increases the time children can spend on education (Brenneman and Kerf, 2002). Also, electricity investments (SDG7) can enable children to study at night which improves their educational performance and, in turn, educational attainment (Collste et al., 2017; Fay et al., 2005; Brenneman and Kerf, 2002). North-South partnerships are needed to provide financial and technical resources to low- and middle-income countries coping with health challenges, particularly those associated with climate change. Likewise, to achieve quality education for all, global 'partnership' with inclusive engagement from diverse stakeholders in all countries is necessary. Policies that emphasize sustainable development and collaboration, in line with SSP1, will lay the groundwork for mutually-beneficial partnerships (Sellers and Ebi, 2018).

3.3 Pathways towards selected SDGs

In Section 3.3, we assess in more detail existing scenario literature on the achievement of a set of selected SDGs, which are under review at the High-level Political Forum (HLPF) 2018: SDG 6, 7, 11, 12 and 15. This includes more in depth insights into the interlinkages from the perspective of these SDGs, important for holistic policy design. We start with SDG 12 as consumption provides a good cross-sectoral entry point (3.1.3). This is followed by resources and basic needs of SDGs 7, 15 and 6. An assessment of pathways related to SDG 11 completes this section.

3.3.1 SDG 12: Responsible consumption and production

SDG 12 relates to several other SDGs. This includes the focus on transformative in the use of key resources (water, energy, food, land, oceans, and climate protection). However, SDG 12 also integrates explicitly the supply- and demand-side perspectives of resource systems (Box 3.2), thus opening the avenue to discuss consumption choices, preference, and lifestyles in the SDG discourse. (SDG 11 on cities being another example of an SDG that lends itself to a discussion from an end-use and demand perspective, Section 3.3.5).

A key concept for SDG 12 is the notion that material wellbeing does not necessarily rely on the utilization ("consumption") of resources per se, but rather on the services and amenities these help to provide (Creutzig et al., 2018b). Wellbeing arises from nutritious and balanced diets rather than from purchase of food items, part of which end-up as food waste even prior to consumption. Likewise, thermal comfort (temperature and humidity control) of a shelter is first of all determined by the characteristics of the building envelope (insulation levels), which then determines the amount of energy needed. For mobility as well, a focus on services and their determinants (e.g., private but also collective decisions such as infrastructure) could lead to different choices. The services and amenities from final consumption (nutrition, thermal comfort, and mobility) require "upstream" services as well: food needs to be produced, goods manufactured and transported buildings and infrastructures built. While this systemic interdependence between demand and supply is at the core of SDG 12, it is ultimately driven by consumption choices.

We need to further disentangle the resource efficiency of end-use and consumption patterns. The resource (i.e., energy) needs ("consumption") for mobility services arises from the combined effects of five interrelated clusters of variables: a) service level demand (e.g., is a trip needed at all), b) individual transport mode choice (e.g., public versus private transport), c) the service efficiency of transport mode usage (e.g., load factors in public transport, or alternative organizational models to individual vehicle ownership such as car sharing that lead to greater asset utilization), and lastly d) the technological (energy) efficiency of the transport vehicle (e.g., a bus or a road vehicle for individual transport services such as a taxi, a car of a car sharing scheme, or a private, individually owned vehicle) and e) the energy source used for the transport vehicle. Ceteris paribus, the levers on resource consumption tend to be larger the closer to the actual service demand the system is leveraged (e.g., avoiding a car trip altogether has a larger impact than switching an internal combustion engine car to biodiesel) (Section 2.3.9). It is important to understand however, that individual choices, while critically important, also face constraints and limitations from the "upstream" supply sectors (industry and businesses) that constrain individual choices with respect to technological and service efficiency. Through innovation and new business models these can also enhance individual choices.

Box 3.2. SDG 12 targets. Source: UN (2015).

12.1	Implement the 10-year framework of programs on sustainable consumption and production, all countries taking action, with developed countries taking the lead, taking into account the development and capabilities of developing countries
12.2	By 2030, achieve the sustainable management and efficient use of natural resources
12.3	By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses
12.4	By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment
12.5	By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse
12.6	Encourage companies, especially large and transnational companies, to adopt sustainable practices and to integrate sustainability information into their reporting cycle
12.7	Promote public procurement practices that are sustainable, in accordance with national policies and priorities
12.8	By 2030, ensure that people everywhere have the relevant information and awareness for sustainable development and lifestyles in harmony with nature
12.a	Support developing countries to strengthen their scientific and technological capacity to move towards more sustainable patterns of consumption and production
12.b	Develop and implement tools to monitor sustainable development impacts for sustainable tourism that creates jobs and promotes local culture and products
12.c	Rationalize inefficient fossil fuel subsidies that encourage wasteful consumption by removing market distortions, in accordance with national circumstances, including by restructuring taxation and phasing out those harmful subsidies, where they exist, to reflect their environmental impacts, taking fully into account the specific needs and conditions of developing countries and minimizing the possible adverse impacts on their development in a manner that protects the poor and the affected communities

Several frameworks exist for steering synergistic strategies of responsible consumption and production:

Avoid/Shift/Improve. A simple concept of "avoid/shift/improve" has been proposed by Creutzig et al. (2018b) to outline generic strategies for more responsible consumption. "Avoid" refers to strategies that avoid resource-intensive systems of service provision altogether such as telecommuting substituting for physical transport. "Shift" refers to strategies substituting resource-intensive systems of service provision by less-resource-intensive ones (e.g., modal choices away from individual transport models to walking and cycling). Lastly, "Improve" refers to strategies of improving technological and service efficiency in service provision (e.g., shared electric vehicles for individual transport).

ReSOLVE. Similar ideas are also expressed in frameworks like "ReSOLVE" (Ellen MacArthur Foundation et al., 2015). ReSOLVE integrates strategies that aim to minimize waste, closing material loops, improve efficiency and asset utilization aiming to Regenerate, Share, Optimize, Loop, Virtualize, and Exchange resource flows and modes of service provision.

3.3.1.1 Over- and under-consumption

The previous discussion of strategies for more "responsible consumption" addresses issues mainly arising from "overconsumption" or inefficiencies in the current systems (Section 2.3.9) but remains largely amiss of a core concern of the SDGs: to redress the current imbalances in access to and the benefits1 of service provision of modern systems of resource use. Billions remain excluded from access to basic services of adequate nutrition, water and sanitation, clean energy services, among others (UN, 2017). Providing basic access to these services by 2030 is consequently a core concern of a number of SDGs and also constitutes the first element to start to define what "responsible consumption" means for those that remain to date excluded from the benefits of modern forms of service provision.

Providing access to basic services and amenities by 2030 for all still begs the question of "what next"? Given the time frame of 2050 for TWI2050, a natural question to pose is: what would constitute "responsible consumption" for the world's poor over a longer time frame that rebalances development aspirations with resource constraints and planetary boundaries? Clearly in a sustainable development context the "overconsumption" model of the Global North cannot be an aspirational goal for the consumers of the Global South. The concept of decent living standards (DLS) aims to assure that people have the material means to pursue a decent life and avoid harm to their basic interests (Doyal and Gough, 1991). Following Rao and Min (2017) these requirements include a set of amenities and services that ensure good health, and those that enable people to engage with society. They include safe and uncramped shelter, nutrition and water, clothing, health care, education and basic comforts in the home, such as lighting and thermal comfort (including water heating), refrigerators and clean cooking devices. These basic comforts serve to avoid harm from extreme weather, disease and pollution. In engaging with society, people seek knowledge about the world, and the means to communicate with others, which give rise to the need for education, devices in the home to communicate (e.g., mobile phones) and access broadcast media (e.g., television), and access to mobility. Rao and Min (2017) provide quantitative guideposts for such a set of amenities and services that support decent standards of living, including inter alia 2500 kcal per day food, 10 m2 per capita floor space, amenities such as a cellphone a fridge and a TV, as well as a minimum of 7000 km/capita per year of mobility. In a scenario exercise inspired by the SDGs (Grubler et al., 2018) have compared the resource implications for aggressive downsizing of the energy system through demand-side technologies with the energy needs for providing DLS for all by 2050. Given persistent heterogeneity and differences between and within countries and subpopulations, assuring DLS of for all also implies that averages need to be substantially higher than minimum values. The conclusion from this scenario exercise is that providing decent standards of living based on the Rao and Min (2017) quantitative framework is possible so long as high levels of leapfrogging in advanced energy systems and electrification in the Global South can be achieved. The greater the extent of the proliferation of the highest standards in waste minimization and technological and service end-use resource efficiency, the more the average living standards can exceed minimum levels (Figure 3.5a) while significantly reducing energy and material resource requirements (Figure 3.5b). Figure 3.5 thus illustrates a globally converging perspective on "responsible consumption" that maintains high levels of material wellbeing while minimizing resource inputs, wastes and pollution. Combining, behavioral change, new business models (e.g., sharing economy) and technological and usage efficiency measures with transformations in upstream sectors under a responsible consumption and production paradigm allows the achievement of high levels of material wellbeing while minimizing resource inputs and wastes.

3.3.1.2 Resource dimensions of SDG 12

Currently SDG 12 comprises 11 illustrative targets (Box 3.2) that combine generic institutional and informational goals with goals related to resource use. These indicators currently however lack specificity, with the exception of goal 12.3 (half global per capita food waste by 2030) as noted by the first scientific review of the SDGs (ICSU and ISSC, 2015). Waste minimization, "environmentally sound management of chemical and wastes", or "rationalization [of] inefficient fossil-fuel subsidies" are further examples of resource-related goals referred to under SDG 12. Here, we adopt a pragmatic approach of assessing various scenarios available in the literature in terms of their illustration of and implications for SDG 12. The appropriate resource flows

[1] Due to international trade impacts and benefits of resource exploitation can be spaced far apart. Over-consumption, that often externalizes its footprints and under-consumption are therefore often interlinked. For an illustration and a scenario of redistribution benefits see e.g., Steffen, W. & Stafford Smith, M. 2013. Planetary boundaries, equity and global sustainability: why wealthy countries could benefit from more equity. Current Opinion in Environmental Sustainability, 5, 403-408.

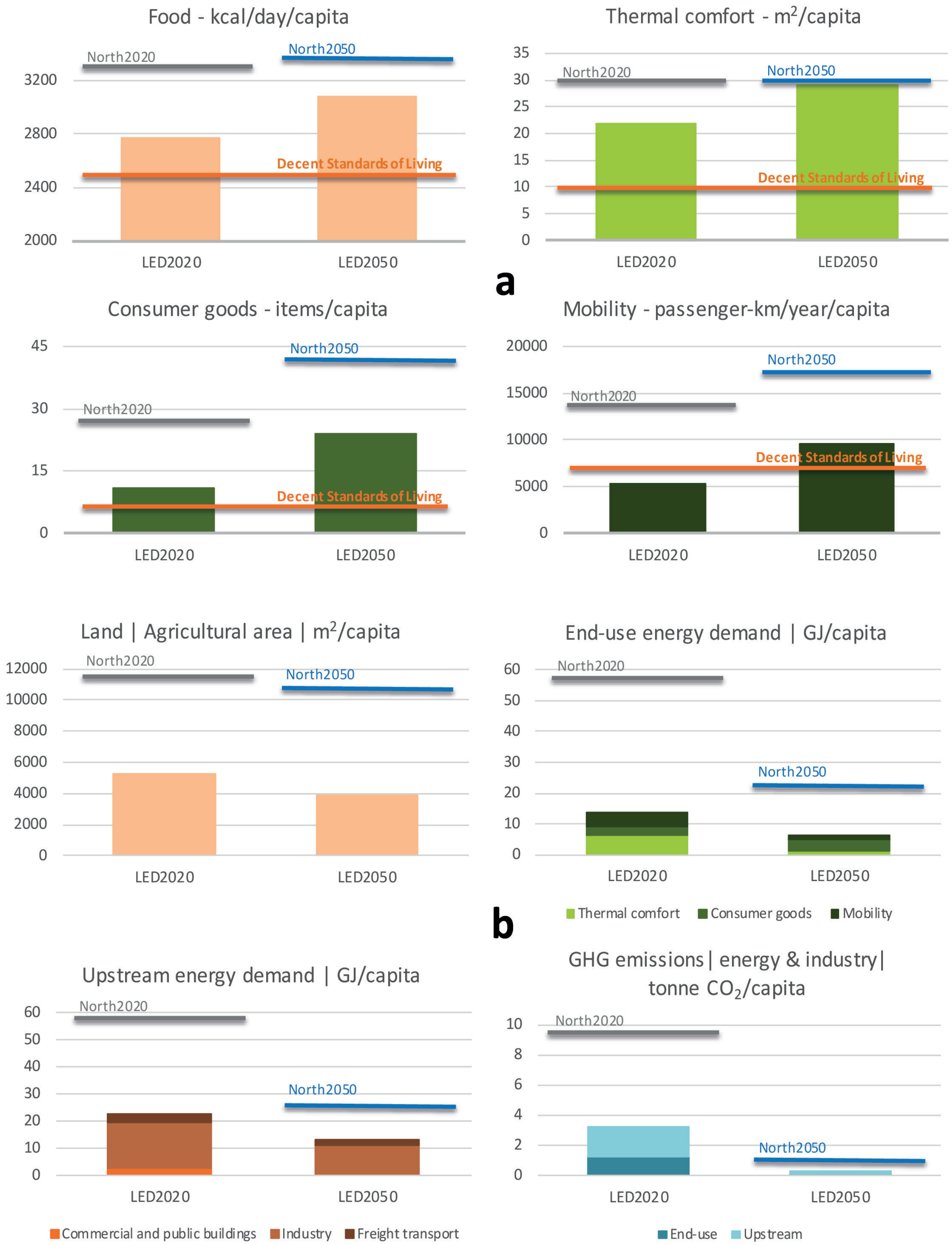


Figure 3.5. Panel a (top). Indicators of per capita material wellbeing for the Global South in 2020 and 2050 in comparison to minima formulated by decent standards of living and per capita values in the Global North. 2050 values are shown for the low energy demand (LED) scenario (Grubler et al., 2018) where high levels of material wellbeing are achieved with the lowest energy and resource consumption levels reported in the scenario literature for 2050. Panel b (bottom). Indicators of per capita resource inputs to meet activity demands (panel a) for the Global South in 2020 and 2050 in comparison with per capita values in the Global North 2020 and 2050. Graphic courtesy of Narasimha Rao and Arnulf Grubler.

to be considered for SDG 12 are those that a) provide a direct service benefits to consumers (e.g., food, or drinking water), are b) key in current models of service provision (e.g., energy, materials for housing, vehicles, appliances, etc.), or c) that while not "consumed" per se by end users are nonetheless strongly influenced by consumption choices in "upstream" sectors, i.e., land resources needed to provide food, fiber, energy, and materials. By looking at a resource matrix, including water, energy, land, and materials2 it is possible to describe the interactions and interlinkages of responsible consumption and production. Given the dominance of climate change mitigation scenarios in the literature available to date, one could also include GHG emissions in this resource assessment matrix (Figure 3.6). Scenarios addressing the elements in the matrix all illustrate the resource implications of integrated systems of production and use combining both the "upstream" resource implications of changing consumption preferences, as well as the "downstream" implication of changed production and end-use service provision patterns that are at the core of SDG 12.

To date there exists not a single scenario illustrating an integrated SDG 12 pathway to 2050 (which TWI2050 is aiming to provide, see Section 3.1.3). Therefore, a selection of scenarios that pertain to SDG 12 are briefly reviewed here and assessed in terms of their SDG 12 resource matrix implications below (Figure 3.6). The review and assessment is necessarily incomplete, reflecting the time and resource constraints of this assessment as well as the limitations of the available scenario literature that has a very strong climate mitigation focus (and a supply-side mitigation options bias in general), and often lacks specificity in reporting consumption patterns (e.g., service levels for housing floor space or mobility) or resource impacts beyond GHGs and energy, with land, and in some instances also materials resource implications reported. Five illustrative scenarios (or clusters of scenario studies) have been identified of particular relevance to SDG 12:

Circular Economy in Europe 2030

This study (Ellen MacArthur Foundation et al., 2015) is a comprehensive assessment of the concept of the circular economy as well as short-term (2030) options for its implementation in Europe, mostly from a business perspective. It mainly assesses the circular economy in terms of economic variables, but provides quantitative scenario and options quantifications for food, mobility, and housing (materials). A valuable specificity of the study is the quantification of takeback (rebound) effects potentially arising from lowered service provision costs in a circular economy.

International Resource Panel, Efficiency plus Climate Mitigation Scenario

This scenario study (Ekins et al., 2017; Hatfield-Dodds et al., 2017)has a focus on material use, embracing an Industrial Ecology perspective and integrating consumption and production perspectives of materials use. Of particular relevance for SDG 12 is the scenario combining high levels of materials efficiency with climate mitigation for which selected end-use consumption for a range of raw materials and energy are reported.

IMAGE Model Scenario and Sensitivity Analysis of End-use Options

Using the IMAGE Integrated Assessment model, a series of studies has explored the implications of reaching a number of SDGs drawing on alternative strategies that include also consumption/behavioral strategies. van Vuuren et al. (2015a) explored the implications of reaching a number (8) of SDG-related indicators. Their "consumption-based" strategy, albeit far from implying drastic changes, suggests that comparable SDG benefits can be achieved via a consumption-based approach, compared to more conventional technology-based strategies. Two studies (Bijl et al., 2017; Stehfest et al., 2009) explored in particular the impact of changing food demand, including also scenarios of dietary shifts and waste reduction that yield significant reductions in global crop demands and corresponding land requirements and agricultural emissions. In van den Berg et al. (2016) an explicit scenario of resource efficiency coupled with climate policies was explored. This scenario is comparable to the scenario presented in Ekins et al. (2017) (see discussion above). The model was also used to look into the relationships between energy, land and water – and the options to reduce pressures on these resources via both increasing efficiency and lifestyle change (van Vuuren et al., 2017). Lastly, a recent model sensitivity analysis (van Vuuren et al., 2018) also includes consumption and demand-side options to explore the potential of reaching an ambitious 1.5˚C climate target without negative emission technologies. The scenario of "lifestyle changes" explored however only assumes marginal changes and as a result its impact is rather small (substituting all negative emission technologies of the baseline 1.5˚C scenario requires to draw on all scenario sensitivity analysis options, including supply-side measures, lifestyle changes, as well as a lower population projection).

IEA ETP B2DS Scenario

The "Beyond 2 Degrees" scenario of the International Energy Agency's Energy Technology Perspectives illustrates the energy and materials resource implications of a scenario significantly below the 2˚C climate target (1.7˚C) and also provides consumption activity level details of the scenario quantification of relevance for SDG 12.

LED (Low Energy Demand) Scenario

This recent scenario exercise (Grubler et al., 2018), using the set of IAMs of IIASA (MESSAGE, GLOBIOM, GAINS), embraces an end-use perspective of reaching an ambitious 1.5^{0}C climate target, with no temperature/emissions overshoot and without relying on negative emissions technologies (CCS, BECCS). Its specifics include an explicit representation of the concept of Decent Standards of Living as well as a rich scenario narrative

[2] This resource matrix was first proposed at IIASA as a method for non-monetary assessment of the resource implications of energy strategies .

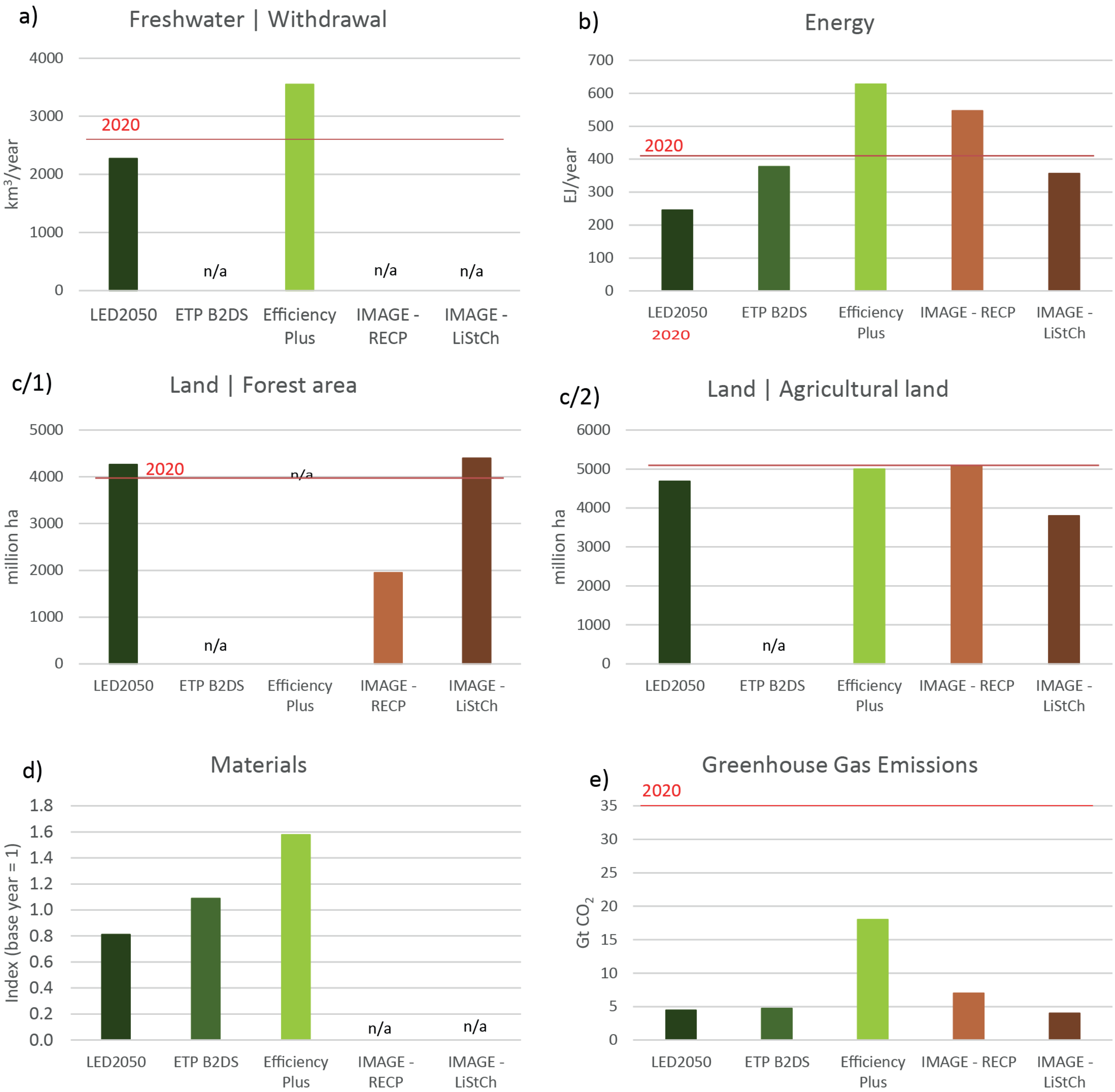


Figure 3.6. Resource impact matrix for water, energy, land, materials and GHGs (industrial sources of CO2) for selected scenarios illustrating SDG 12 at the global level. (Regional indicators are currently not reported comprehensively in the published scenario literature). Note in particular that ceteris paribus the lower the resource impacts of a scenario, the higher its SDG 12 benefit. Scenarios pictured: LED = Low Energy Demand scenario (Grubler et al., 2018) in case of water withdrawal LED is represented by the "integrated SDG" scenario (Parkinson et al. 2018, based on Grubler, et al. 2018), ETP B2DS = IEA's Energy Technology Perspectives, Beyond 2°C Scenario (IEA), Efficiency Plus = Efficiency Plus scenario of the International Resource Panel (Ekins et al., 2017; Hatfield-Dodds et al., 2017), which is a combination of their Resource Efficiency and Ambitious Climate scenarios, RECP = Global resource efficiency and climate policy scenario of IMAGE (van den Berg et al., 2016), LiStCh = Life Style Change scenario of IMAGE (van Vuuren et al., 2018). Panel a) Scenario data for water are currently mostly unavailable. Panel b) Direct equivalence method has been used to transform available primary energy scenario data to desired final energy metric (using implied efficiencies in the LED scenario for 2050). Panel c/1) LED: total forest area includes managed, natural and harvested area; Efficiency Plus scenario is based on Ekins et al. (2017) Fig. 108 that reports a range of literature values incl. IPCC AR5; RECP scenario: includes exploited forest and plantation forest as reported in van den Berg et al., 2016, Fig.4.; LiStCh scenario: includes all forests as reported in van Vuuren et al, 2018, Fig 3.a. Panel c/2) LED: agricultural land includes total cropland, pasture, and harvested area; Efficiency Plus is based on Ekins et al., 2017, Fig. 105, which uses data from various sources by adapting UNEP (2012); RECP scenario: includes grassland, bioenergy crops, and arable land as reported van den Berg et al., 2016, Fig.4.; LiStCh scenario: includes energy drop, pasture and crop land as reported in van Vuuren et al., 2018, Fig 3.a. Panel d) Materials included in the different scenarios: LED: steel, aluminum, cement, paper, petrochemicals, other, feedstock; ETP: cement, high value chemicals, ammonia, methanol, crude steel, paper, aluminum; Efficiency Plus: biomass, fossil fuels, metal ores, non-metallic minerals. Graphic courtesy of Arnulf Grubler and Benigna Boza-Kiss.

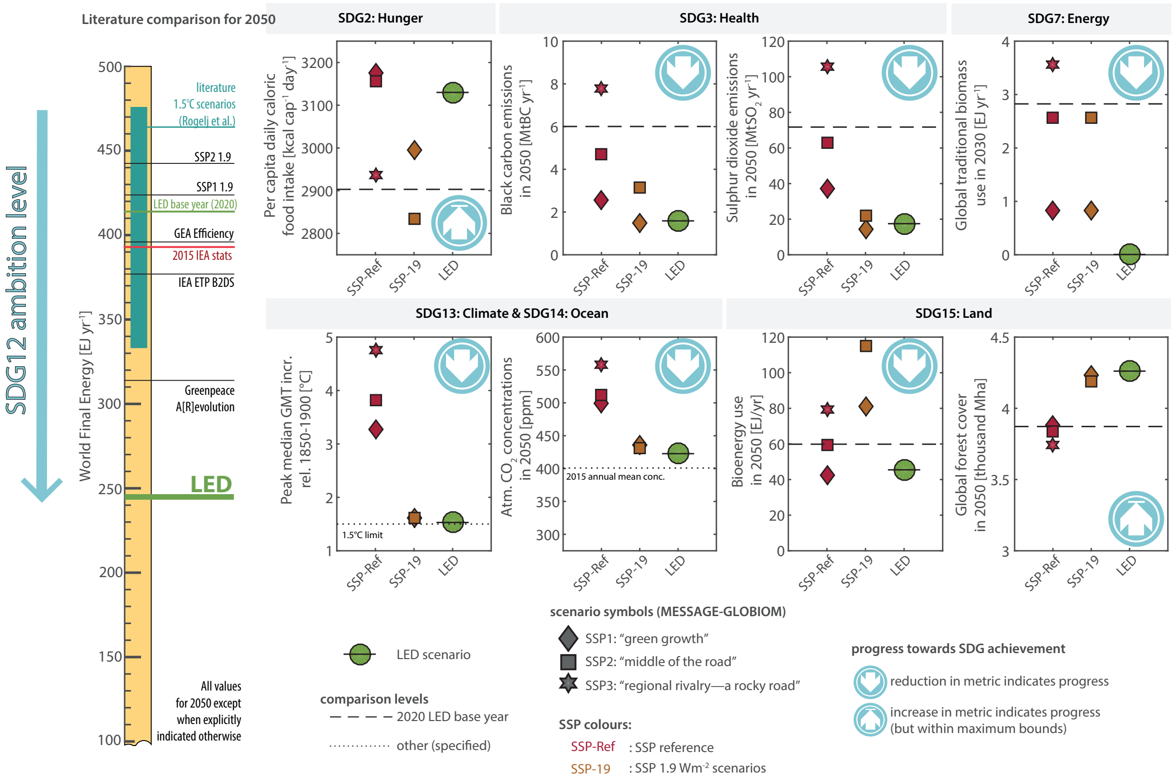


Figure 3.7. Scenario comparison of SDG synergies and co-benefits of illustrative SDG 12 scenarios. Arrows show desirable direction for various SDG indicators. Note that currently consistent SDG indicators are available only for a subset of scenarios. Source: After Grubler et al. (2018).

in which new trends in ICT convergence, digitalization, and sharing economy concepts translate into step changes in materials and energy efficiency from an end-use perspective leading to rapid decarbonization at end-use that in turn drives upstream decarbonization.

3.3.1.3 Synergies and trade-offs with other SDGs

Although a comprehensive assessment of synergies and trade-offs of SDG 12 versus other SDGs remains outstanding and will require the development of further scenario and modeling studies, some preliminary conclusions are nonetheless possible. First, the higher the degree of fulfillment of the SDG 12 tenets of responsible consumption and production can be achieved (Figure 3.6), the higher will be the co-benefit on other SDGs. Lessening resource impacts and wastes allows not only the reduction of environmental burdens and the furthering of the goals of related SDGs on water, biodiversity, climate and oceans, but also stands to free the resources for addressing poverty and aiming at a more equitable distribution of material wellbeing. This main conclusion is illustrated in Figure 3.7 below, where indeed the highest synergies and co-benefits are achieved in the scenarios of highest degree of resource efficiency and waste minimization. The LED scenario with the highest SDG 12 benefits also generally scores highest on six other SDGs suggesting that responsible consumption and production might indeed be a synergistic entry point for many other SDGs as well. Second, the available evidence of potential trade-offs between SDG 12 and other SDGs is currently too sparse to draw any firm conclusion from. Impacts on labor markets and so-called "rebound" (takeback) effects[3] are often mentioned as potential trade-offs in scenarios of low resource inputs.

Evidently, moving from current systems to more resource-efficient ones, embracing concepts from the circular and the sharing economy, might reduce the demand for certain products and commodities (e.g., individually owned vehicles), but in turn they also create new job opportunities. A first quantification of the employment effects of a circular economy for Europe (EU-27) by 2030 suggests overall net employment benefits with job losses in raw materials sectors (extraction and processing) and in some manufacturing sectors (consumer durables, vehicles) more than compensated by new job creation in waste recycling and new manufacturing jobs (Ellen MacArthur Foundation et al., 2015). The largest labor market impact is estimated to arise from the indirect effect of higher consumption induced by significantly lower prices for materials and energy in a circular economy scenario (Ellen MacArthur Foundation et al., 2015).

The same study however also estimates the potential rebound effect from lessened resource prices in a circular economy in Europe to be rather small: €0.3 trillion by 2030, which corresponds with between 4% of current resource costs (€7.2 trillion Euro) to 6% of total resource costs by 2030 (€5.4 trillion) (Ellen MacArthur Foundation et al., 2015) compared to a typical range of potential rebound effects of 5% to 30% (Sorrel, 2007). A

[3] Rebound effects describe potential increases in consumption after realized cost savings. E.g. a more fuel efficient car reduces mobility costs, savings of which might be used to purchase more mobility services (driving longer distances).

scenario sensitivity analysis performed by (Grubler et al., 2018) suggests that the SDG benefits of low resource consumption of their LED scenario could be preserved even with 50% higher demands, suggesting the potential trade-offs from potential rebound effects to be rather small.

3.3.2 SDG 7: Affordable and clean energy

The overarching aim of SDG 7 is to "ensure access to affordable, reliable, sustainable and modern energy for all". Underpinning this grand objective are targets with respect to access to modern energy, efficiency improvement and renewable energy (Box 3.3).

The impacts of energy production and consumption can be far-reaching, certainly with respect to environmental impacts. This means that pathways need to also to comply with climate goals, for instance (SDG 13 and Paris Agreement). The scientific community thus has a critical role to play here in improving the science underlying the key relationships.

3.3.2.1 Key characteristics of pathways achieving SDG 7 and SDG 13

Ensuring universal access to affordable, reliable and modern energy services (SDG 7.1) can be translated into universal access to electricity and to clean cooking by 2030. Achieving these two targets implies that yearly, around 92 million people obtain access to electricity and 190 million people start relying on clean fuels and cooking technologies annually (IEA, 2017). According to the scenario literature, cost-efficient provision of electricity access could rely mainly on decentralized solutions, both mini-grid (35%) and off-grid (26%), which are the most viable options in rural and remote areas where basic energy needs still have to be met (Dagnachew et al., 2018; IEA, 2017; Pachauri et al., 2013). Renewable sources would play a major role in such cases, covering up to 84% and 92% of the additional electricity demand in mini-grid and off-grid applications, respectively (solar PV is the most promising technology for both mini-grid and off-grid solutions) (IEA, 2017). The remaining additional electricity demand (39%) would need to be supplied by the grid, which is more fossil-intensive than the other options (37% of energy mix). The investment necessary to guarantee a universal minimum electricity household consumption (500 kWh in urban and 250 kWh in rural areas) amounts to 725 billion US$ for the period 2017-2030, with sub-Saharan Africa being the main recipient (IEA, 2017).

Considering the heterogeneity in electricity access, from basic (e.g., lighting) to complex energy services (e.g., air conditioning or productive use applications), it is worth noting that off-grid solutions play a major role (80% of electricity supply) in scenarios; however, the more complex the services demanded, the more important is the role of grid and mini-grid solutions (respectively 68-75% and 25-16% of electricity supply), whereas off-grid solutions are less cost-effective (Mentis et al., 2017; Pachauri et al., 2013). The target daily per-household electricity requirements and assumptions on supply technologies determine much of the variation in the assessment of cumulative investment needed: between $US\$_{2005}$ 9 and $US\$_{2005}$ 12 billion every year for guaranteeing 420 kWh per household per year in rural areas (Pachauri et al., 2013) or between US$12 and US$134 billion considering an average consumption between 100 and 456 kWh per household per year in urban areas and between 50 and 360 kWh per household per year in rural areas (Bazilian et al., 2010).

The universal access to clean, reliable and modern energy for cooking implies a shift in the fuel mix away from traditional biomass towards gas (35%), LPG (30%), electricity (17%) and improved biomass (16%) (IEA, 2017). Compared to electricity access, lower investments are required (US$61 billion), but the outcome is more uncertain. The main hindering factors, affordability constraints on new more efficient appliances and cultural preferences, call for a targeted polices at local and community level (IEA, 2017). Also in this case, investment range estimates differ widely: 38-50 billion $US\$_{2005}$ yearly between 2010 and 2030 (Pachauri et al., 2013) and 1.4-2.2 US$ yearly (Bazilian et al., 2010). Past experience has shown that the most effective policies combine support for fuel prices with grant/loans for purchasing more efficient stoves (Pachauri et al., 2013).

Achieving SDG target 7.1 may have implications on energy demand. The sign and magnitude strongly depend on compliance of energy sector with a greener fuel mix (SDG target 7.2), on efforts to speed up energy efficiency improvement rates in all sectors (SDG target 7.3), and ultimately on the actions

Box 3.3. SDG 7 targets. Source: UN (2015).

- **7.1** By 2030, ensure universal access to affordable, reliable and modern energy services
- **7.2** By 2030, increase substantially the share of renewable energy in the global energy mix
- **7.3** By 2030, double the global rate of improvement in energy efficiency
- **7.a** By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology
- **7.b** By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States, and land-locked developing countries, in accordance with their respective programs of support

adopted to combat climate change and its impacts (SDG 13). The optimal pathway for achieving the SDG target 7.1 (considering some improvements also in targets 7.2 and 7.3) shows that expanding electricity access leads only to a small rise of residential energy demand (1%-2% by 2030 with respect to a "no new policy scenario"); however, the high efficiency of modern energy appliances can completely offset this, shrinking energy use by 31-46% (Pachauri et al., 2013). When some mitigating actions (SDG 13) are added to the policy mix, the universal energy access can still be achieved by 2030 with even lower energy requirements (17% lower with respect to energy demand in the "current policy scenario") through a radical transformation of production and consumption patterns (IEA, 2017).

Pursuing efforts to limit the temperature increase to well below 2°C above pre-industrial levels (Holz et al., 2018), which is implicitly at the core of SDG 13, will require a dramatically reshaping of the global energy system, leading to net-zero carbon emissions by mid-century. Achieving the three targets of SDG 7 can help, but more ambitious actions will need to follow post-2030. A strong contraction of CO_2 emissions can be achieved through a progressive phase-out of fossil-based power generation: more than 70% of electricity will likely need to be produced with low-carbon technologies in 2030 (nearly 100% in 2050), and the power sector will need to satisfy a growing share of energy demand (around 25% in 2030 and 42% in 2050). Meanwhile, the transport sector could register a contraction of yearly emission up to 70% in 2050, industrial sector up to 100%, and residential sector more than 600% with respect to 2010 levels (Rogelj et al., 2015).

3.3.2.2 Synergies and trade-offs with other SDGs

McCollum et al. (2018a) assess the scientific literature exploring the impacts that the kinds of energy solutions enumerated by SDG 7 (renewables, efficiency, energy for the poor) could potentially have on the various other SDGs, or vice-versa the effects that actions and policies in these other domains could have on the energy SDG targets. The authors score the target-level interactions identified – in terms of whether it is positive or negative and to what extent – by employing the typology and seven-point scale presented in Nilsson et al. (2016). Earlier synthesis-type papers exploring selected energy-related SDG interactions include, among others, (Fuso Nerini et al., 2017; Aether, 2016; Jakob and Steckel, 2016; Lim et al., 2016; von Stechow et al., 2016; Raji et al., 2015; von Stechow et al., 2015; Aranda et al., 2014; Shaw et al., 2014; Bhattacharyya, 2013; Pueyo et al., 2013; Saunders et al., 2013; Smith et al., 2013a; WBGU, 2013; Riahi et al., 2012; Cook, 2011). Figure 3.8 summarizes the interactions identified in the energy literature on an SDG target-by-target basis. It should be noted, however, that it is difficult to assign unequivocal scores. The assessment shows that SDG 7 has strong relationships with several other SDGs. In many cases, there are rather positive interactions between SDG 7 and the other SDGs, indicating that positive interactions might outweigh negative ones, both in number and magnitude. Examples include sustainable urban development (among other reduction of air pollution), climate change (reduction of CO2 emissions), development of marine and terrestrial biodiversity (among others via reduced climate change), eradication of poverty and hunger and decent work and economic growth (via provisioning of energy services), and good health and wellbeing (provisioning of energy services and reduction of air pollution). Trade-offs, on the other hand, were identified

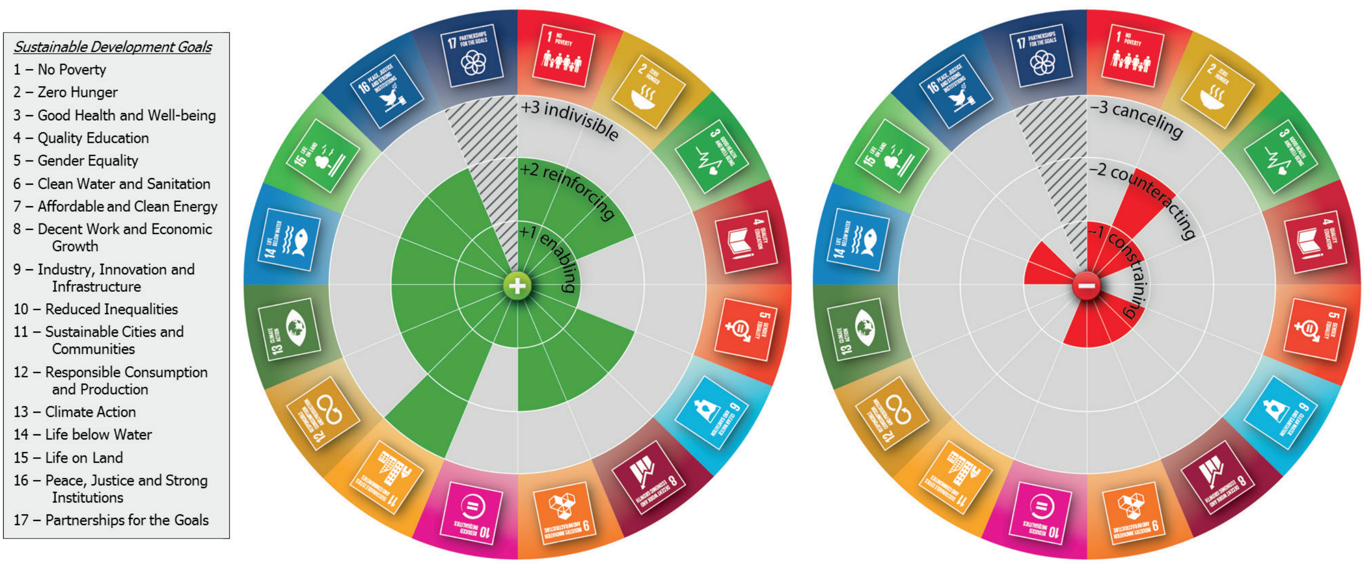


Figure 3.8. Nature of the interactions between SDG 7 (Energy) and the non-energy SDGs. Licensed under CC-BY 3.0 by McCollum et al. (2018a). The relationships may be either positive (left panel) or negative (right panel) to differing degrees. See Nilsson et al. (2016) for definitions pertaining to each score from +3 (positive) to –3 (negative) in integer increments. The absence of a colored wedge in either the left or right panels indicates a lack of positive or negative interactions, respectively; if wedges are absent in both panels for a given SDG, this indicates a score of 0 ('consistent'). Only one positive or negative score is shown per SDG; in instances where multiple interactions are present at the underlying target level (positive and negative treated separately), the individual score with the greatest magnitude is shown. Note that, while not illustrated by this figure, some SDG linkages may involve more than simple two-way interactions (e.g., the energy-water-land 'nexus'). No scoring is done for the "means of implementation" SDG 17.

in particular for SDG 2 (via the production of bioenergy). Large-scale 2nd generation bioenergy deployment is a key element of 1.5°C and 2°C transformation pathways (SDG 7 and SDG 13) (Schleussner et al., 2016; Rogelj et al., 2015). However, large-scale bioenergy production might have negative sustainability implications and thus may conflict with the SDGs, especially with climate (Popp et al., 2014) and biodiversity protection, food and water security (Bonsch et al., 2016) as well as environmental pollution (e.g., nitrogen). does not show any trade-off between climate mitigation and universal modern energy access objectives; in this case two opposite forces are at play. According to Cameron et al. (2016), mitigation efforts increase energy costs for the poor: e.g., in South Asia plus 44% by 2030 under stringent climate mitigation with respect to no climate policy case. Moreover, mitigation policies can spur greater efficiency, both in electricity production and end-use appliances, which results in lower electricity demand. A recent study analyzing universal electrification scenarios for sub-Saharan Africa estimates that while electricity prices are likely to be higher in scenarios that include climate mitigation polices, the total investments required for achieving universal electricity access could be 20% lower than in a "no climate policy" case (Dagnachew et al., 2018).

3.3.2.3 Policies that maximize synergies and minimize trade-offs

There is a positive and reinforcing feedback between policies targeting SDG 7, in particular target 7.1, and poverty and malnutrition alleviation, better health and education perspectives, less risks and more opportunity for women. The SDG targets 7.2 and 7.3 can boost economic growth reducing the impact on the environment.

Trade-offs may arise among SDGs and policies focused on achieving one single target can go to the detriment of others. This is the case of large-scale bioenergy production that are part of the energy mix transformation required by SDG target 7.2. On this purpose, policies boosting renewable energy production should also foresee environmental protection measures such as forest or water conservation schemes. However, more level of interactions and feedback needs to be accounted when designing a policy because regulating one environmental externality of bioenergy production may again interfere with other SDGs (Humpenöder et al., 2018): bioenergy production coupled with forest protection, deforestation and associated emissions decline substantially may increase food prices (Popp et al., 2011), 3.3.3. Another strategy to align large-scale bioenergy production with the SDG agenda is the implementation of measures reducing the pressure on land in general (land-sparing measures). Tilman et al. (2011) showed that, indeed, trade-offs between bioenergy production and other sustainability trade-offs (such as deforestation, CO_2 emissions from land-use change, nitrogen losses) can significantly be lowered by improved agricultural productivity or reduced consumption of resource-intensive livestock products combined with less household waste (Humpenöder et al., 2018; Smith et al., 2013b).

Even SDG 7 and SDG 13, which look mutually reinforcing, hide some trade-offs: climate policy can in some cases hinder universal access to energy. Therefore, when designing climate policies additional interventions to shield the poor from potential price rises need to be adopted. Research for South Asia (Cameron et al., 2016) suggests that a combination of fuel subsidies on cleaner cooking fuels and grants or microfinance for the purchase of cleaner and more efficient stoves can be effective in making these more affordable for poor households even in the face of steep increases in fuel prices caused by stringent climate mitigation policies. Other options include pro-poor tariffs, or cross-subsidization to protect the poor from any potential electricity price increases. Evidence from many Asian and Latin American nations (Borges da Silveira Bezerra et al., 2017)suggest that shielding the poor from potential energy price rises may also be achieved through non-energy policies. Wider social assistance programs such as targeted and conditional cash transfers, minimum income schemes, or other safety nets can also be effective in shielding the poor from potential price changes and making modern energy services more affordable to them.

3.3.3 SDG 15: Life on land

Land use to provide essential natural goods and resources is one of the foundations of human wellbeing (de Fries 2004). The evolving food needs of a population of about 9-10 billion people (in 2050) (Lutz et al., 2018) has to be met. Historically, increasing demand has led to expanding the cultivated agricultural area and with a technological revolution that has increased yields through increases in modern inputs such as irrigation water, improved seeds, fertilizer, machinery and pesticides. But land is a limited resource that has to fulfill multiple functions, including protecting biodiversity. Moreover, other SDGs imply that the environmental impacts of food production need to be mitigated (Section 3.3.3.3). Climate change will strongly affect agricultural yields, freshwater availability and biodiversity. Such potential future pressures on the land system would pose huge challenges for the sustainability both of agricultural and forestry production and of terrestrial and aquatic ecosystems and the services they provide to society, endangering the achievement of SDG 15 targets (Box 3.4).

3.3.3.1 Key characteristics of pathways achieving SDG 15

Foley et al. (2011) suggest sustainable land use will have to 1) cut greenhouse gas emissions from land use and agricultural production; 2) reduce biodiversity and habitat losses; 3) decrease unsustainable water withdrawals; and 4) control nitrogen pollution. As environmental preservation and sustainable use of the Earth's terrestrial species and ecosystems are strongly related, recent scenario studies have evaluated interconnections among the above key aspects and show pathways to a global sustainable future of land use (Humpenöder et al., 2018; Erb et al., 2016; Obersteiner et al., 2016; Popp et al., 2014; Foley et al., 2011). Most of these studies agree that a wide option space exists to achieve a sustainable global land use in the future. Effective en-

Box 3.4. SDG 15 targets. Source: UN (2015).

15.1 By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands, in line with obligations under international agreements

15.2 By 2020, promote the implementation of sustainable management of all types of forests, halt deforestation, restore degraded forests and substantially increase afforestation and reforestation globally

15.3 By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world

15.4 By 2030, ensure the conservation of mountain ecosystems, including their biodiversity, in order to enhance their capacity to provide benefits that are essential for sustainable development

15.5 Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species

15.6 Promote fair and equitable sharing of the benefits arising from the utilization of genetic resources and promote appropriate access to such resources, as internationally agreed

15.7 Take urgent action to end poaching and trafficking of protected species of flora and fauna and address both demand and supply of illegal wildlife products

15.8 By 2020, introduce measures to prevent the introduction and significantly reduce the impact of invasive alien species on land and water ecosystems and control or eradicate the priority species

15.9 By 2020, integrate ecosystem and biodiversity values into national and local planning, development processes, poverty reduction strategies and accounts

15.a Mobilize and significantly increase financial resources from all sources to conserve and sustainably use biodiversity and ecosystems

15.b Mobilize significant resources from all sources and at all levels to finance sustainable forest management and provide adequate incentives to developing countries to advance such management, including for conservation and reforestation

15.c Enhance global support for efforts to combat poaching and trafficking of protected species, including by increasing the capacity of local communities to pursue sustainable livelihood opportunities

vironmental protection of forest and water resources in combination with land-sparing measures (such as agricultural intensification and dietary change) are key for feeding a growing population while mitigating the pressures on land and other sustainability goals (Figure 3.9).

The protection of the environment (such as forest and water) can directly contribute to avoid the current unsustainable use of land. Around 40% of land is used for agriculture (Foley et al., 2011) and 15% of land is currently under protection (UNEP-WCMC and IUCN, 2016), but that does not cover all areas important for biodiversity. 70% of total freshwater withdrawal is used for providing food which is responsible for 80% of total water consumption (WWAP, 2012) (Section 3.3.4). The heavy use of fertilizers and animal waste is a major driver of the global nitrogen cycle anthropogenic intervention. Environmental protection is needed to strengthen natural resource management. Land protection would protect the Earth's terrestrial ecosystems and key biodiversity areas. Improved water-use efficiency would reduce water demand while improved nitrogen management would reduce nitrogen requirement and loss (Muller et al., 2017; Bodirsky et al., 2015). For example, nitrogen pollution or loss can be avoided by removing the nitrogen from livestock manure, sewage and household waste such as wasted food, and recycling it on the field as well as low-input farming systems, such as organic agriculture.

Agricultural technological innovation can significantly contribute to improve efficiency of land, food, and water systems, compensate for restrictions on agricultural expansion and reduce the pressure on the environment under the given food demand for feeding growing population (Humpenöder et al., 2018; Obersteiner et al., 2016; Popp et al., 2014; Foley et al., 2011). Recent studies suggest that sufficient food or nutrient (protein) can be provided without increasing cropland area by increasing crop yields (Mauser et al., 2015; Tilman et al., 2011) and with massive trade volumes (Billen et al., 2015). However,

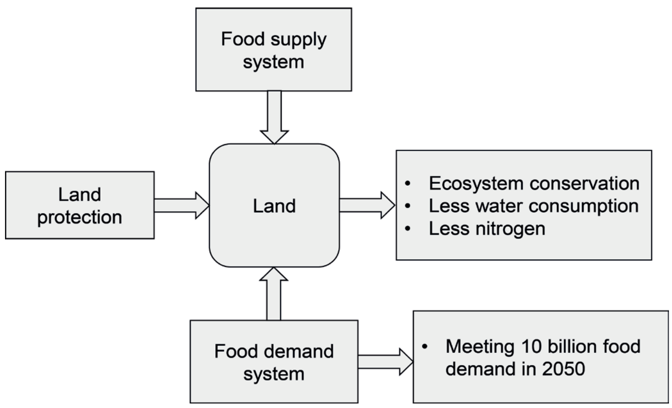


Figure 3.9. Overview of the characteristics of good future of land. Graphic courtesy of Tomoko Hasegawa.

there is still a large gap between potential yields and current actual yields (Foley et al., 2011). Most of the yield gaps is in the regions where productivity may be limited by poor management. There are significant opportunities to increase yields across many parts of Africa, Latin America and Eastern Europe, where nutrient and water limitations seem to be strongest (Foley et al., 2011). Transfer of high-efficiency production technologies including advanced crop species and improved management for existing crop varieties from other regions should contribute to close the yield gaps, while improvements in crop species including genetic modifications will probably increase potential yields into the future. In addition, grazing intensification and efficiency gains in global livestock systems have also been identified as a crucial element because of their large feed requirements and an enhanced use of crop-based concentrate (Weindl et al., 2017a; Weindl et al., 2017b; Havlik et al., 2014). However, knowledge is still limited due to the very limited data availability and the huge range of uncertainty related to the extent and intensity of grazing on the global scale (Erb et al., 2016; Herrero et al., 2013). Changes in consumption patterns (3.3.1) are another key determination for sustainable land and food systems. Dietary change such as less meat and reduced food waste can lower demand for food, feed, water, and other resources and then reduce the pressure on land and the environment (Erb et al., 2016; Obersteiner et al., 2016; Hasegawa et al., 2015; Bajželj et al., 2014; Stehfest et al., 2009). Currently, mainly in developed regions, actual food consumption is much above the recommended (maximum) dietary requirement corresponding to the energy needs of an individual at the maximum acceptable Body Mass Index, engaged in vigorous physical activity (FAO, 2015). Excessive food consumption can be reduced by putting taxation on animal-sourced food (e.g., red meat) or unhealthy food which have been introduced in attempt to overcome increasing

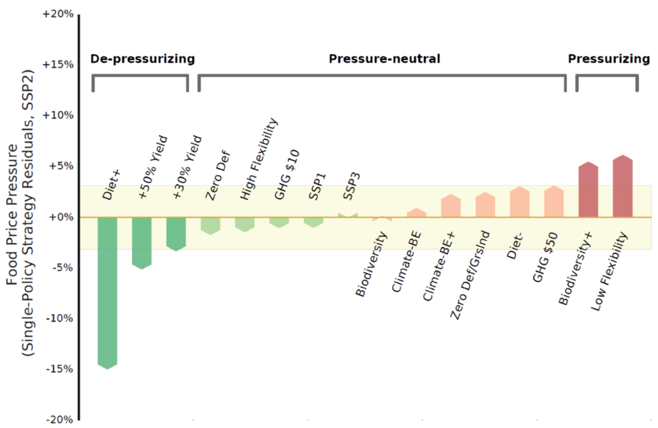


Figure 3.10. A synergy and trade-offs between possible land-based options and food prices. Source: Obersteiner et al., 2016. CC-BY-NC 4.0. Climate-BE: Moderate bioenergy and nuclear energy: ΔT < 2°C; Climate-BE+: High bioenergy and no nuclear: ΔT < 2°C; Low (High) flexibility : slow (rapid) production system shifts and high (low) waste; +30% (+50%) yield: nominal input-neutral yield growth + 30% (+ 50%); Zero Def(/Grslnd): no gross forest loss (or grassland loss); Biodiversity: Moderate protection of biodiversity hotspots; Biodiversity+: no conversion of biodiversity hotspots; GHG US$10(US$50): LULUCF emissions tax: US$ 10/tCO2eq (US$50/tCO2eq); Diet-: Western diet globalization; Diet+: Reduced meat demand.

obesity rates and improving health in some countries (e.g., Colchero et al. (2016)). In addition to dietary change, consumption structural change are expected to substantially contribute to feed the projected world population without compromising environmental sustainability (Hasegawa, in preparation) and (Billen et al., 2015). If an equitable human diet is established within countries and globally, the environmental impacts associated with feeding the future growing population can be reduced or even becomes positive (Hasegawa, in preparation). Combining policies, such as food support targeted on the undernourished accompanied with reducing overconsumption and food waste, would reduce food production and contribute to sustainable use of land by reducing water demand, deforestation and land-use change emissions and bring benefit to food security and human health by reducing obesity and related diseases.

3.3.3.2 Synergies and trade-offs with other SDGs

Measures and policies for preserving and sustainably using the Earth's terrestrial species and ecosystems (SDG 15) are strongly related with other SDGs. Land and water protection schemes for preserving and sustainably using the Earth's terrestrial species can indeed decrease deforestation, associated emissions and biodiversity loss (SDGs 13 and 15) whereas it can increase competition for land and hence affect food security via increased food prices (SDG 2) and climate action via increased bioenergy prices (SDG 13) (Humpenöder et al., 2018; Popp et al., 2011; Wise et al., 2009). In addition, land protection schemes focusing on one single land-use type such as forests could lead to displacement effects into non-forest land-use types which also could contain high carbon and biodiversity value (Popp et al., 2014). Regeneration of natural ecosystems via e.g., afforestation could have beneficial effects on carbon uptake (SDG 13) (Humpenöder et al., 2014; Strengers et al., 2008). However, this beneficial effect for climate could be eaten up by biophysical drivers such as albedo (Arora and Montenegro, 2011; Bathiany et al., 2010).

Agricultural intensification schemes may help reduce cropland expansion and deforestation and avoid biodiversity loss (SDG 15), while also benefiting food security by lowering food price (SDG 2), and mitigating climate change through reducing CO_2 emissions from land-use change and decreasing bioenergy prices (SDG 13) (Humpenöder et al., 2018; Obersteiner et al., 2016). However, agricultural intensification may be associated with higher agricultural inputs and can cause environmental pressures such as nitrogen contamination (Humpenöder et al., 2018; Obersteiner et al., 2016; Billen et al., 2015) and higher water use (SDG 6) (Humpenöder et al., 2018; Obersteiner et al., 2016).

Diet change towards less meat-intensive diets and reducing food waste (SDG 12) and mitigating land pressure (SDG15) contribute to decrease food prices (Figure 3.10), mitigate completion on food and provide global food security (SDG2) (Humpenöder et al., 2018; Obersteiner et al., 2016; Bajželj et al., 2014). It also contributes to climate change mitigation through leading to lower land-use change CO_2 emissions (SDG 13) (Springmann et al., 2016b; Stehfest et al., 2009). In addition, dietary changes to less meat or plant-based protein could promote human health (SDG 3) and climate mitigation (SDG 13) (Springmann et al., 2016a; Stehfest et al., 2009). These global food transition would reduce the agricultural production and cropland and pasture expansion, resulting in a large carbon uptake from regrowing vegetation and substantial reduction in methane and nitrous oxide emission (SDG13). In contrast, without any complementary policy, some negative side-effects of dietary change would occur on livestock farmers who will face income losses which might be an important barrier in implementing low-meat diets (Stehfest et al., 2009). Moreover, equitable food distribution and globally converging diets need more international trade which would decreases self-sufficiency of many developing regions with regard to their local needs for food and nutrient (Erb et al., 2016; Billen et al., 2015).

3.3.3.3 Policies that maximize synergies and minimize trade-offs

A holistic perspective and combination of multiple measures and policies is needed to solve the current unsustainable development trajectory. As many challenges are strongly interrelated with each other, single options are prone to involve trade-offs among multiple sustainability goals (Humpenöder et al., 2018) (Figure 3.11). For example, a combination of agricultural intensification with forest and water protection schemes, nitrogen mitigation measures and improved fertilization efficiency would be needed to avoid the side-effects of agricultural intensification on water use and nitrogen pollution (Humpenöder et al., 2018; Bodirsky et al., 2014). Moreover, a combination of supply and demand-side options would be effective to avoid the side-effects of a single-side option. For example, low-input farming systems (such as organic agriculture and reductions food-competing feed from arable land) accompanied with reduction of food waste would contribute to reduce the side-effects of lower productivity due to low-input farming system. Regarding negative effects of dietary change on livestock farmers, revenue from taxing resource-intensive food or unhealthy food would bring a significant source of new income which could be used for diet programs including development of new income opportunities for the affected farmers. With regard to food insecurity associated with forest protection and climate mitigation, international aid or domestic income transfer is expected to offset such adverse side effect attaining stringent climate stabilization.

A number of policy options exist for dealing with specific negative effects of unsustainable land use. Clearly enforced and controlled nature protection areas can limit agricultural land expansion. Public and private investment in agricultural technologies, especially plant breeding, has shown very high economic returns (Lotze-Campen et al., 2014). Emission taxation can effectively reduce air pollution and greenhouse gas emissions. Water pricing can help to improve water-use efficiency (Section 4.4.1). However, these specific policy measures have to be better coordinated and need to be made coherent across sectors.

We reviewed studies that assess sustainability of land and food systems and represent the state-of-art knowledge about the sustainable future of land, effects of policies, and pathways to sustainable development. Many studies show many optional spaces to realize such future. Current change is not enough. A new dynamic innovation with combining the effective multi-sectoral measures (Section 4.4.3.1) would be needed. This includes a strong coordination among the various policy measures to induce the technological and organizational changes needed for achieving multiple sustainability goals.

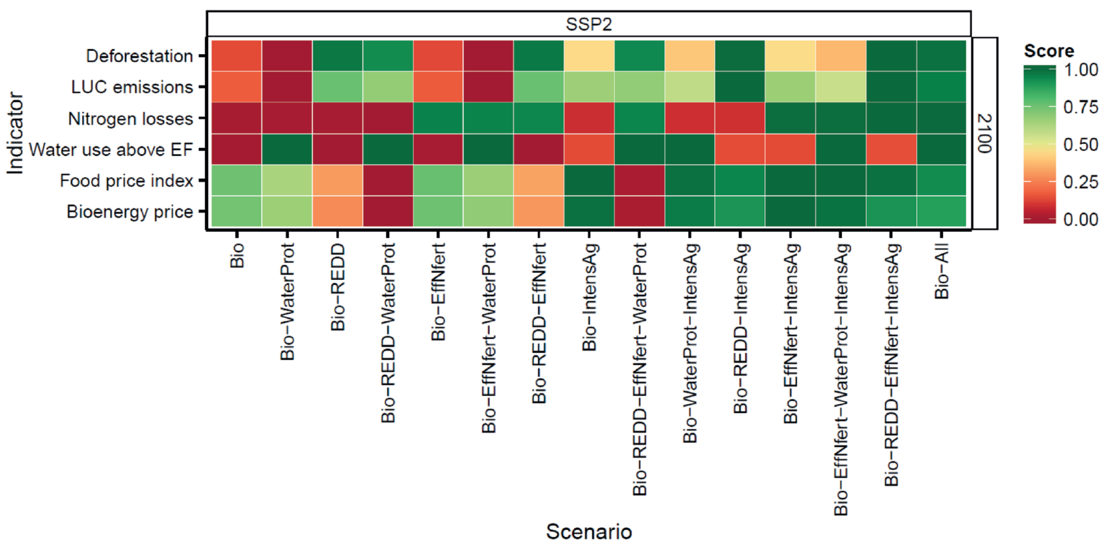


Figure 3.11. The global option space matrix for the year 2100. Licensed under CC BY 3.0 by Humpenöder et al 2018. REDD: forest protection by putting a price on CO_2 emissions from the conversion of forests and other carbon-rich ecosystems; EffNfert: improved soil nitrogen uptake efficiency; WaterProt: protection of water resources based on environmental flow requirements; IntensAg: higher food and bioenergy crops yields and higher livestock productivity; All: combination of REDD, EffNfert, Water-Prot and IntensAg.

3.3.4 SDG 6: Clean water and sanitation

The overarching objective of SDG 6 is to ensure the availability and sustainable management of water and sanitation for all. The SDG 6 targets are presented in Box 3.5. This section overviews the building blocks needed for moving towards a global pathway consistent with SDG 6, the interactions with other SDGs and the policies for maximizing synergies and offsetting trade-offs.

It is estimated that more than 2.1 billion people remain without access to a type of improved water source, and that more than 1.7 billion lack access to improved sanitation (UNICEF and WHO, 2017). Moreover, in developing countries, almost 90% of sewage is discharged without any treatment (WWAP, 2012), while some developed countries also continue to release wastewater to the environment without sufficient treatment (Baum et al., 2013). Recent analysis suggests that almost 36 million hectares of irrigated cropland (about 10% of the global irrigated area) exists in catchments with high levels of dependence on urban wastewater flows (Thebo et al., 2017). Another recent analysis suggests that projected socioeconomic development to 2030 will leave more than 3.5 billion people without sufficient access to piped water and wastewater infrastructure needed to meet SDG 6 (Figure 3.12) (Parkinson et al., 2018).

At the same time, the volume of water being used by humans continues to increase. Global water withdrawals in 2010 were estimated to have reached 4000 km3 (FAO, 2016). The agricultural sector withdrew approximately 67%, followed by the industry (23%) and domestic (10%) sectors (Flörke et al., 2013). About 12% of the industry and domestic withdrawals was consumed globally and 88% was discharged back into the environment (Flörke et al., 2013). There is significant regional diversity, depending on the development of water recycling. Global scale assessments anticipate growth of water demands to between 6,000 and 8,500 km3 by 2050 (Bijl et al., 2016; Wada et al., 2016; Hejazi et al., 2014). Much of this increased demand will occur in urban areas, placing strain on surrounding water resource systems (McDonald et al., 2014).

3.3.4.1 Key characteristics of pathways achieving SDG 6

To achieve SDG 6, a massive investment in water supply, sanitation and wastewater treatment will be required. When water demand outstrips the available resource in a given area, water scarcity ensues, causing increased pressure and potential shortages for water users. It is estimated that approximately four billion people currently live in areas facing severe water scarcity for at least one month of the year (Mekonnen and Hoekstra, 2016), and that this number could grow to reach almost six billion by 2050 if unmitigated. Besides physical water availability, other key determinants of water scarcity include water quality, water access, the cost of transporting and storing water, institutional constraints and governance (e.g., user prioritization schemes), and the competition for water across alternative uses (Vanham et al., 2018; Jaeger et al., 2017; van Vliet et al., 2017). Climate change can worsen water scarcity as well.

The concept of water wedges (Figure 3.13) can help combining different strategies that could together reduce the population living with water scarcity (Wada et al., 2014). It shows that increasing access to water supply and sanitation does not only depend on increasing supply using infrastructure measures – but also increasing the efficiency of water use.

Key technologies for increasing water availability and accessibility to meet these new demands depend on region or country. Groundwater can be an attractive water source (as opposed to extracting water from nearby rivers) because it is less sensitive to climate variability. However, about 1.7 billion people live in areas where groundwater resources and/or

Box 3.5. SDG 6 targets. Source: UN (2015).

- **6.1** By 2030, achieve universal and equitable access to safe and affordable drinking water for all
- **6.2** By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations
- **6.3** By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally
- **6.4** By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity
- **6.5** By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate
- **6.6** By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes
- **6.a** By 2030, expand international cooperation and capacity building support to developing countries in water- and sanitation-related activities and programs, including water harvesting, desalination, water efficiency, wastewater treatment, recycling/reuse technologies
- **6.b** Support and strengthen the participation of local communities in improving water and sanitation management

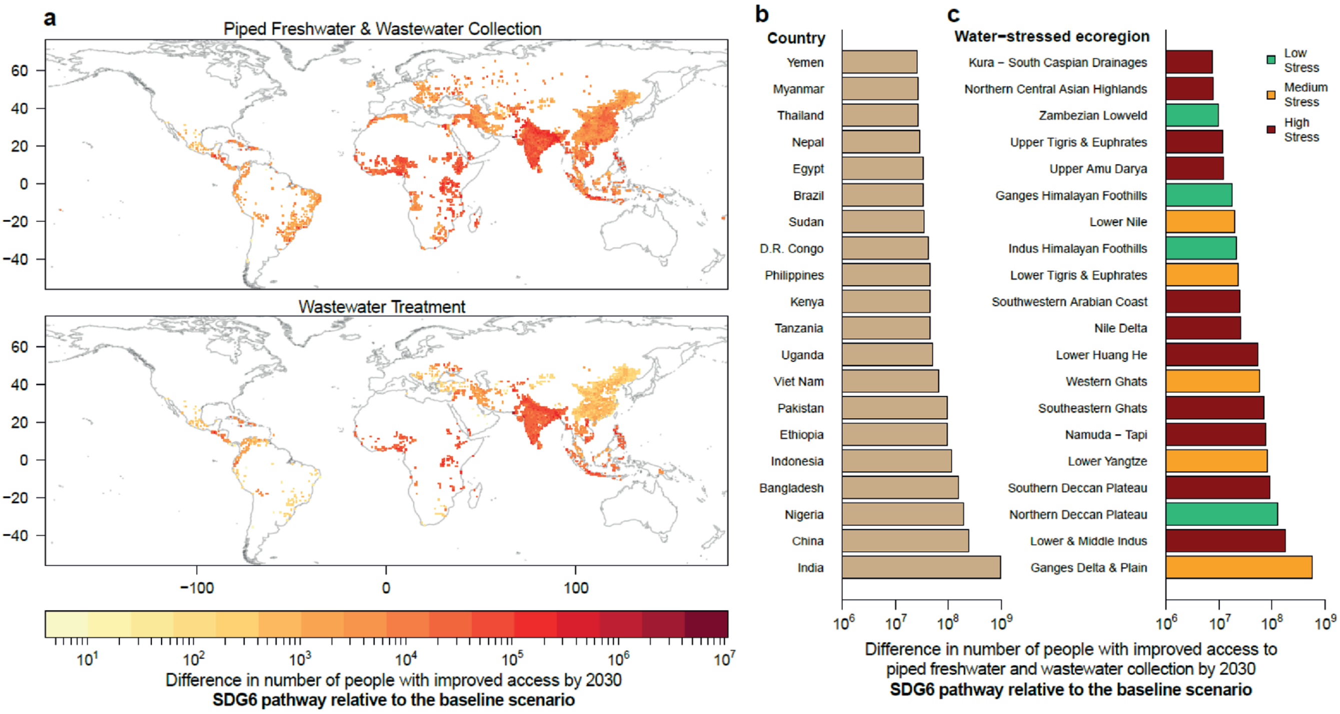


Figure 3.12. Number of people requiring piped water access and wastewater treatment in 2030 under an SDG 6 pathway relative to a baseline (business-as-usual) human development scenario: a. spatially-explicit results; b. results aggregated by country; and c. results aggregated by ecoregion. Licensed under CC-BY-NC by Parkinson et al. (2018).

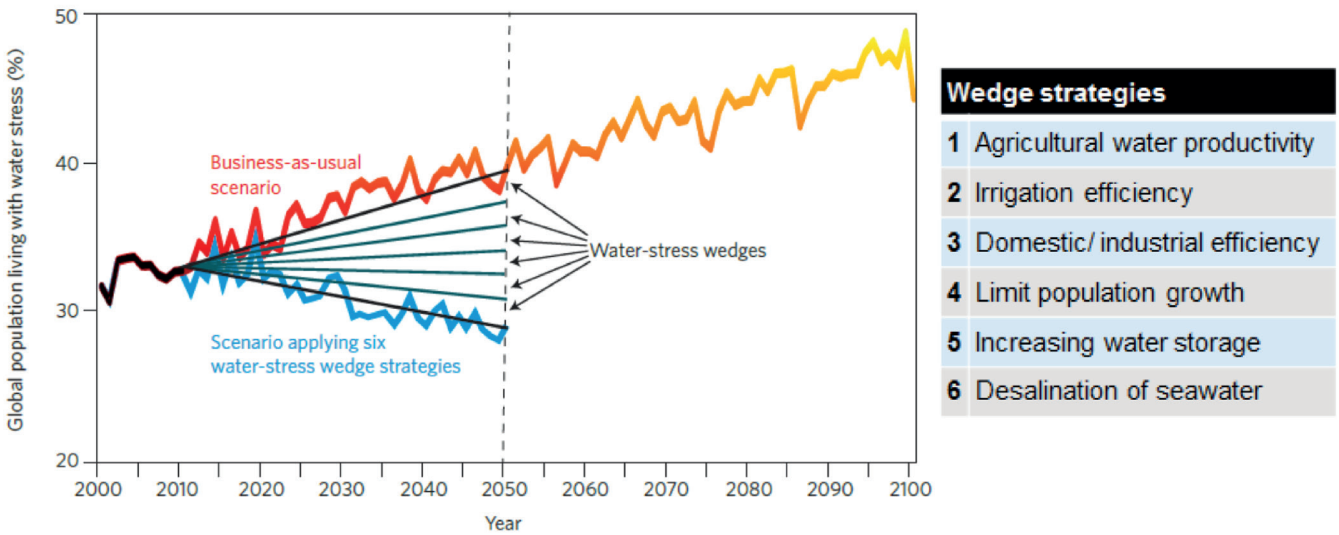


Figure 3.13. Strategies for reducing water stress. Source: after Wada et al. (2014).

groundwater-dependent ecosystems are already under threat (Gleeson et al., 2012), and impacts of groundwater extraction on long-term groundwater availability can be difficult to monitor due to limited ground monitoring worldwide. Recent research proposes possible indices and standards for ensuring groundwater sustainability (Gleeson and Richter, 2018; Wada and Bierkens, 2014). Packaged water has emerged as an effective approach to ensure improved water access in developing urban areas facing scarcity due to a lack of existing water infrastructure (Vedachalam et al., 2017).

Water efficiency measures provide a crucial lever in this framework because such measures are usually the least-cost option for addressing water constraints (as opposed to expanding water supply). For example, it is anticipated that switching to more efficient irrigation methods in many regions could provide a substantial amount of water to support future urban demand growth in water scarce areas reducing water competition among different sectors (Bijl and al, 2018; Flörke et al., 2018; Jägermeyr et al., 2016). Likewise, a significant amount of water is lost during water distribution due to leakage and evaporation, and prioritizing refurbishment can improve water availability and reduce risks of water contamination (Lee and Schwab, 2005; LeChevallier et al., 2003).

As water flows vary from year-to-year due to both climatic variability and changing human influences such as reservoir regulation and land-use change, it is important for water resource managers to develop adaptive ground- and surface water strategies. Increased water storage capacity can also reduce water-related hazards such as floods. Specifically, many developing regions require storage to manage challenging hydrology brought about by variable flows and drought conditions (Grey and Sadoff, 2007). Expanding water storage capacity by developing new reservoirs is a contentious issue because of the associated impacts to land availability and shifts in the natural flow regime in up- and downstream rivers (Liu et al., 2018; Grill et al., 2015). However, small to medium sized storage systems could provide a better solution in some regions. In addition, managed aquifer recharge through intelligent irrigation practices (e.g., flooding fields during the off-season) or direct injection into aquifers could provide an alternative means for increasing storage capacity without consuming additional land (Niswonger et al., 2017). The performance of many existing reservoirs should also be enhanced by reducing sedimentation built-up over many years of reservoir operation (Wisser et al., 2013) or by optimizing the location of new reservoirs (Schmitt et al., 2018; Kondolf et al., 2014).

The SDG 6 targets involving water quality and ecosystem protection are to be partially addressed by mitigating water scarcity, because this will ensure sufficient flows in rivers and aquifers (van Vliet et al., 2017; Liu et al., 2016a). However, expanded access to wastewater treatment will be needed to ensure water quality. Expanding wastewater treatment capacity can be expensive. Nevertheless, there are both centralized and decentralized solutions to choose from, with costs and benefits dependent on the specific location (Kavvada et al., 2016; McDonald et al., 2016). It should be noted that treated domestic wastewater unsuitable for municipal water supplies may be perfectly suitable for industrial cooling and landscape irrigation (Stillwell and Webber, 2014; Grant et al., 2012). Direct wastewater recycling can be achieved in this context by cascading water uses, but this will only be possible if there exists capacity and willingness to distinguish wastewater flows and apply them elsewhere (Terpstra, 1999). Wastewater recycling technologies are thus a critical component of SDG 6 pathways because they simultaneously address quality, efficiency and scarcity indicators.

Desalination can also provide needed freshwater security in water scarce regions, but should be viewed as a complementary option in the sense that it is used once all other potential sources of water supply and of managing water demand (e.g., through water pricing or water saving technologies) are exhausted. This is because desalination is expensive, can require a significant amount of energy, and produces waste in the form of brine that must be managed separately to mitigate environmental impacts (Sommariva, 2010). Moreover, desalination can result in thermal pollution, posing a risk to marine ecosystems. Despite these challenges, there are many industrial applications where desalination technologies provide the means to safely treat highly contaminated flows (Shaffer et al., 2013).

Wastewater treatment will promote improved sanitation (SDG target 6.2) by protecting downstream users from harmful water-borne illnesses. Universal access to improved sanitation is an important component of SDG 6 because it is closely linked with access to clean water. The World Bank outlines a number of different options and provide a recent economic analysis for achieving the water access and sanitation targets (Hutton and Varughese, 2016). The assessed options include providing piped water to houses in both urban and rural areas, collection and treatment of wastewater using centralized technologies, and the use of distributed pit latrines and septic systems for wastewater management. It is estimated that between 61 and 123 billion dollars per year of spending will be needed to meet the 2030 targets for drinking water, sanitation and hygiene.

A key step in achieving the SDG 6 targets is more integrated and transboundary water resources management. However, in many regions transboundary management is complicated by difficult political tension brought about by historical conflicts between countries and regions, e.g., the Nile and Indus basins (Tawfik and Dombrowsky, 2018; Swain, 2017). Overcoming political disputes along the road towards effective transboundary management is perhaps the most challenging aspect of achieving the SDG 6 objectives (Subramanian et al., 2014). However, some positive progress towards this target has occurred in many European basins, and to some extent for instance in the Mekong, coordinated by the Mekong River Commission (Schmeier, 2012).

3.3.4.2 Synergies and trade-offs with other SDGs

Water is a basic service, making the water-access targets ingrained in SDG 6 fully integrated with the objective to reduce poverty (SDG 1). Without clean water and adequate sanitation, it is difficult to achieve good health and wellbeing. Moreover, as women often travel long distances to obtain water from unimproved sources, this time is not available to them for other purposes such as education (Graham et al., 2016). Improved sanitation services can also help to protect women's health and safety (Fisher, 2008).

Water availability is also linked intimately to the agriculture and energy system. Increasing agriculture production often requires more water consumption. At the same time, increasing irrigation and fertilizer use could lead to greater water stress and degraded water quality in some regions (Nilsson et al., 2017). Some low-carbon energy technologies consume significant amounts of water (e.g., irrigated bioenergy feedstocks) or may impact flow regimes (e.g., hydropower), while some clean water technologies are energy-intensive. These characteristics can create trade-offs between clean water and targets of SDG 7 and climate mitigation (SDG13) (Humpenöder et al., 2018; Fricko et al., 2016; Parkinson et al., 2016a; Hejazi et al., 2015). Mitigating climate change will help to stabilize hydro-climatic systems driving water resource availability around the world.

There are important linkages between water and SDGs related to prosperity and poverty as well. Developing and managing water resources and infrastructure will leads to more jobs (SDG8). Areas facing water security challenges also typically face stagnated economic growth (Grey and Sadoff, 2007). Water is a critical input for many industrial processes with implications for water availability and quality (Flörke et al., 2013) and economic output. Reduced inequality at higher overall income levels is likely to lead to greater demands for water resources because historically increased income leads to more consumption (Parkinson et al., 2016b). However, reduced inequalities are likely to also enable populations to more effectively implement advanced technologies and integrated management options. Cities and communities that are sustainable will require universal access to clean water and sanitation, and stable water supply and quality. Likewise, sustainability measures taken across all sectors will include avoiding impacts to water resources and water-related ecosystems.

Preventing marine pollution contributes to improving water quality. Marine and coastal conservation can support integrated water resource management and will help to protect water-related ecosystems and vice-versa (Nilsson et al., 2017). Terrestrial ecosystems can become polluted from poor quality water, and thus water quality targets in SDG 6 are consistent with SDG 15. Management of forests and other land-use types in line with SDG 15 impacts water storage, water quality and aquifer recharge (Guse et al., 2015).

SDG 6 objectives for integrated and transboundary management are consistent with the SDG 16 targets for reduced human conflict. Cooperation across countries (SDG 17) and sectors, as well as increased access to financing will be critical towards ensuring sufficient investment in water infrastructure for developing regions and transboundary water management.

3.3.4.3 Policies that maximize synergies and minimize trade-offs

Integrated valuation of end-use water and energy efficiency measures and coupled planning of supply-side projects will ensure long-term development meets multiple targets (Parkinson et al., 2016a; Bartos and Chester, 2014). For example, cascading water uses can ensure wastewater recycling is achieved in an energy-efficient way (Grant et al., 2012). Agricultural and trade policies that shift food production from water-stressed regions will help to achieve water scarcity targets (Flörke et al., 2018; Davis et al., 2017), and promoting organic farming practices (i.e., minimal fertilizer use) will protect water resources (Reganold and Wachter, 2016). Water pricing reforms in certain regions will boost allocative efficiency while ensuring affordability for the poor (Burdack et al., 2014). Basin-scale planning and data sharing in transboundary basins will be critical for coordinated management and benefit sharing for conflict prevention (Arjoon et al., 2016; Dombrowsky, 2009). Moreover, institutional reforms will support implementation of integrated water resources management (Horlemann and Dombrowsky, 2012). Presumptive environmental flow standards will avoid water scarcity and protect ecosystems (Gleeson and Richter, 2018; Wada and Bierkens, 2014). Managed aquifer recharge and other so-called 'nature-based solutions' are important options for supporting increased storage and wastewater management capabilities without developing new infrastructure (Sonneveld and Alfarra, 2018; Niswonger et al., 2017; Drewes, 2009).

3.3.5 SDG 11: Sustainable cities and communities

SDG11 on sustainable cities and communities directly interacts with the livelihoods of people. It addresses the most tangible assets of daily living, including housing, mobility, basic services, and the quality of life, which are also covered by other SDGs. With urbanization, SDG 11 also confronts one of the megatrends of the 21st century. By 2050, close to 70% of the world population will live in cities, and 90% of this increase will happen in Asia and Africa (UNDESA, 2018). This all-to-obvious observation is nonetheless of incredible importance, as it points to not only improving current urban infrastructures and living, but also to designing sustainable cities and urban areas that are currently build. SDG 11 also is the most spatially-explicit SDG in that spatial context determines access to affordable housing, transport and green spaces. Spatial design and interplay play hence a crucial role in achieving this SDG.

3.3.5.1 Key characteristics of pathways achieving SDG 11

The specific targets of SDG 11 are listed in Box 3.6. A pathway characterization cannot however start with a purely quantitative specification of outcomes, but also needs to understand both processes, power and context-dependence that is rooted both in the diversity of cities and their inhabitants and power relations. Collective praxis with collaborative dialogs are hence an important tool and empowering principle for sustainable urbanization (Peake, 2016). In fact, participatory processes improve the likelihood of inclusive and resource-efficient projects (Fernandez Milan and Creutzig, 2015). Successful SDG 11 pathways hence require a participatory approach that avoids one-size-fits-all solutions and standardization (e.g., the urban planning ideas of Le Corbusier) or simple characterization in a few dozen quantitative parameters (such as the ratio of road space to residential area). Instead, the pathways will start with processes that give voice to those in vulnerable situations and those commonly excluded from decision making processes. Paradoxically, participatory processes also require strong leadership of municipal agents that set the setting and infrastructure for dialog and collective action not only at municipal but also on communal levels. It will also require leadership at communal level that use participatory processes to empower neglected people in their communities.

Pathways for sustainable cities in 2050 involve targets that go beyond those detailed in Box 3.6. To structure those, this section now focuses on the dimensions of housing, mobility, and urban form, aiming to achieve inclusion of vulnerable populations, climate-proofing/resource-efficiency, and avoiding local pollution. While not capturing all targets of SDG 11 equally, this 3x3 matrix is nonetheless a useful tool for structuring the TWI2050 pathway.

By 2014, more than 880 million urbanites lived in slums (UN Habitat, 2016). At current trends indicate, urban population is expected to raise by 2.500 billion from about 4.2 billion inhabitants in 2018 to 6.7 billion inhabitants in 2050 (UNDESA, 2018). Hence, adequate urban housing for more than three billion people will need to be provided in the next 30 years to meet SDG 11 targets. Strategies to provide shelter include a) slum upgrading (which can be very challenging to achieve without expelling poor populations to worse locations via gentrification processes); b) re-modularizing existing housing stock to avoiding demographic lock-in (e.g., seniors remaining stuck in big houses after children have moved out); and c) new building stock. If housing units will in average by occupied by four tenants, then about 400-600 million new housing units will need to be provided by 2050, or 13-20 million per year. These are best provided in compact environments, limiting floor space while offering high accessibility and designed in resource-efficient manner (e.g., promoting wood-based materials instead of cement and steel) and matching technologies. Such design can offer up to 44% saving in terms of life-cycle energy compared to the counterfactual default case (Mastrucci and Rao, 2017).

Lack of accessibility is a concern in cities on all continents, characterized for example by a pushing out of poor and middle-class inhabitants to urban peripheries in, for example Paris and Berlin, by transit deserts in US cities, and by lack of mode-choices in African cities, where walking remains often the only option. Access to cities has been mapped in spatial detail, highlighting the African continent (Weiss et al., 2018). However similar maps for intra-city accessibility are missing, and are an important challenge for research. Safety is a crucial component of accessibility (World Bank, 2017).

The urban form emerges from the spatial relation between buildings and transport networks. Urban design considerations deserve extra emphasis as they capture important complements to housing and mobility. In general this concerns the design of public space that is inviting for people to stay, or in other words, the capability of designing cities at human scale (Gehl, 2013). This involves safe street design, e.g., by proper lighting and high visibility to prevent crime and violence. It also includes green spaces for recreation and urban cooling, counteracting urban heat island effects and mitigating deadly heat waves. Especially in arid zones, this involves the design of narrow street canyon providing shadow and channeling wind for cooling. It will be crucial to design these options at community and micro-scale not only for rich neighborhoods, but especially for poorer communities to offset existing disadvantages (Fernandez Milan and Creutzig, 2015).

Long-term urbanization pathways have recently been discussed and their importance has increased in line with the international recognition that there is an urgent need to integrate sustainable strategies into national and local development plans. Due to the complexity of urban systems, however, system integration for implementation of plans requires a novel framework involving interdisciplinary approaches. The Urban Climate Change Research Network has introduced five pathways which provide a foundational framework for climate actions for cities. This includes disaster management, reduction of greenhouse gas emissions, governance, and institutional networks (Rosenzweig

Box 3.6. SDG 11 targets. Source: UN (2015).

11.1	By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums
11.2	By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons
11.3	By 2030, enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries
11.4	Strengthen efforts to protect and safeguard the world's cultural and natural heritage
11.5	By 2030, significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses relative to global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations
11.6	By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management
11.6	By 2030, provide universal access to safe, inclusive and accessible, green and public spaces, in particular for women and children, older persons and persons with disabilities
11.a	Support positive economic, social and environmental links between urban, peri-urban and rural areas by strengthening national and regional development planning
11.b	By 2020, substantially increase the number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, resilience to disasters, and develop and implement, in line with the Sendai Framework for Disaster Risk Reduction 2015-2030, holistic disaster risk management at all levels
11.c	Support least developed countries, including through financial and technical assistance, in building sustainable and resilient buildings utilizing local materials

et al., 2018). WBGU (2016) has examined the great transformation towards sustainability, and tried to clarify the challenges and opportunities looking at the areas where urbanization trajectories require fundamental changes.

Cities are recognized as powerful drivers of global environmental change. In order to develop methodologies for sustainable long-term pathways for cities, the coherence of macro and micro level societal transformation also needs to be taken into account. The SSPs describe five alternative societal transitions

Box 3.7. Case Study: Alternative sustainable scenarios: Tokyo SSPs interlinked with SDG 11.

Tokyo has experienced huge urbanization during a period of high economic growth, from the 1960s to the 1980s. However, in the sprawling edge of the city, the population gradually has shrunk, and urban functions have begun to decrease. There have also been additional concerns about the deterioration of old infrastructures. Making up the core of the megacity region, Tokyo has very complex social functions and expectations for a sustainable vision. Therefore, Tokyo sustainable pathway (SSP1) has been developed with some alternative sustainable goals. The main focuses are i) social and cultural vitality, wellbeing, ii) efficiency, and iii) self-sufficiency. Through a technical scenario writing method, two scenarios have been developed for SSP1, namely Local Vitality (Happiness) scenario, and efficiency scenario (Kamei et al., 2016). Local Vitality scenario emphasizes social equity, basic social services, good quality of urban amenities, and local cultural assets. On the other hand, the efficiency scenario focuses more on advanced technology and efficient lifestyles. In order to achieve SDG 11, the integration of both scenarios is required. However, some quantitative analysis also projects that the Local Vitality scenario can also achieve high-level efficiency by applying efficient technology and novel thinking on lifestyles. SDG 11 targets require the factors of inclusive social welfare, social diversity, and human capital as well as efficient use of social materials. Therefore, Local Vitality scenario has huge potential to realize SDG 11 in the case of Tokyo (Kamei et al., submitted)(Figure 3.14). It requires more investments on renovating existing infrastructures and maintaining safe and good quality local public services. More research into investigating trade-offs and synergies of compact and dispersed development, e.g., considering PV deployment (Yamagata and Seya 2013), can further elucidate the specific characteristics of promising pathways.

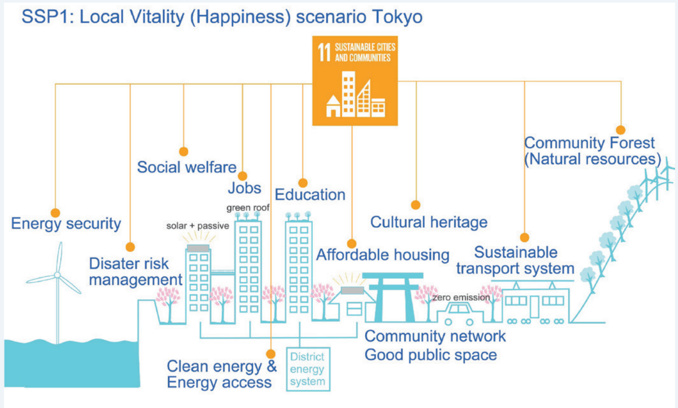


Figure 3.14. SSP1 Local Vitality (Happiness) scenario Tokyo. Graphic courtesy of Miho Kamei.

Box 3.8. Case Study: Dynamic urbanization prospects: Bhutan SSPs interlinked with SDG 11.

Bhutan is a rapidly growing country. It has developed and adopted a unique Gross National Happiness (GNH) index for national policy strategies. Rapid urbanization is beginning to occur, which is likely to lead to a number of large developments and densely populated areas, potentially causing the expansion of social disparity and social segregation, along with the destruction of natural resources and local identities. Therefore, conserving local areas is a key factor for SSP1: Sustainability scenario which represents decentralized urbanization strategies. On the other hand, SSP2: Business-As-Usual scenario assumes an increase of highly populated areas. This Sustainability scenario might be seen as a contradiction to efficient urban growth strategies, however, this is an important point which suggests each city and region requires their own pathways which fit to a specific local context. There is large potential to reconsider how to achieve an efficient lifestyle. In the case of Bhutan, traditional industries and local agriculture, and natural resources are vulnerable assets which have to be maintained by local inhabitants. This traditional spirit has cultivated a unique local context. It should be noted that these assets are also significant targets in SDG 11 (Figure 3.15). This Sustainability scenario is linked with GNH indicators specifically cultural diversity, community vitality, and ecological diversity. Local governance and institutional partnership also need to be well organized.

Figure 3.15. Bhutan SSP1: Sustainability scenario. Graphic courtesy of Miho Kamei.

in a global world which were constructed with mitigation and adaptation measures (O'Neill et al., 2017), Section 3.1.2. SSP1, for instance, represents the most ideal future pathway called 'Sustainability'. By linking with SSPs, urbanization factors (e.g., demographics) can be projected by applying downscaling approaches (Terama et al., 2017). For the sake of identifying sustainable visions for each different city, SSPs-cities can be developed that are also applicable for quantitative projections (e.g., building, transport, and material flow) based on the alternative pathways (Kamei et al., 2016). Two case studies and interactions with SDG 11 are shown in Box 3.7 and Box 3.8.

3.3.5.2 Synergies and trade-offs with other SDGs

There are relationships between the development of cities and most other SDGs. For instance, urban infrastructures shape consumption patterns (SDG 12). The fast-growing urbanization trend, in particular in Asia and Africa, will result in a growing need for new urban infrastructures, providing huge challenges but also opportunities. The choices made, due to the longevity of the nature of urban infrastructure (in particular for transport and buildings systems) introduces path dependency effects shaping consumption patterns for the coming decades and even century. For instance, urban planning affects travel distances the attractiveness of low-carbon transport modes and reduced heating and cooling needs. Alternative buildings approaches could include less floor space per person, alternative material use and modified production process of materials in, for example, the steel and cement sector (Creutzig et al., 2016; Muller et al., 2013).

The majority of the final energy use occurs within the urban environment, creating strong interlinkage with SDG 7 and related synergies and trade-offs (Section 3.3.2). While in developing countries more energy per capita is consumed in urban areas due to on average higher income, in industrialized countries the more compact urban form combined with the availability of public transport infrastructure results in lower final energy use on average than in sub-urban or rural areas (Grubler and Fisk, 2012). Urbanization also influences the challenge to provide modern energy for all, as less infrastructure is needed. At the same time, however, it does provide a strong link with air pollution.

Access to clean water and sanitation (SDG 6) is a key issue to sustainable cities, and closely linked to public health, especially the prevention of infectious diseases. A recent investigation of SDG 6 found that all of its six targets have strong synergies with SDG 11, and indeed that SDG 11 has most synergies of all other SDGs with SDG 6 (Fernandez Milan and Creutzig, 2017). However cities with higher population growth, especially those in sub-Saharan Africa, also have the lowest rate of access to clean water and sanitation (Fernandez Milan and Creutzig, 2017).

Changing the use of existing as well as new urban infrastructure through modal shift, building retrofitting, using state of the art design principles, improved public transit systems could reduce GHG emission with 27-57% in 2050 (SDG 13). Combined with low-carbon production of urban infrastructure, (which is a commonly underestimated issue) emissions would further reduce to 45%-68% (Creutzig et al., 2016). Informal settlements (often within the city environment) are particularly vulnerable for climate related hazards such as flooding. Climate impact can be mitigated and resilience improved by urban design features such as vegetation corridors, green parks, reed bed and low lying areas that can soak up water, when integrated in the build environment while contributing to biodiversity and carbon storage (Bai et al., 2018).

3.3.5.3 Policies that maximize synergies and minimize trade-offs

In essence, the combination of SDG 11 with the other SDGs discussed requires the provision of access to shelter, mobility, and energy for all at adequate levels, while keeping material consumption and GHG emissions at bay, helping to avoid the crossing of planetary boundaries (Rockstrom et al., 2009).

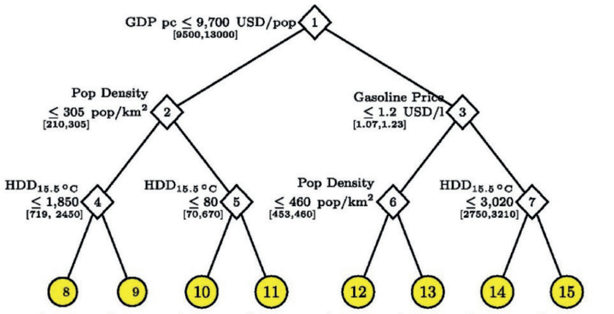
The most important policy instrument to achieve is most likely taxes on fuels (or the GHG emissions in fuels), identified as crucial long-term driver of energy-efficient urbanization both by empirical data analysis of cities worldwide (Creutzig et al., 2015), and by theoretical urban economic modeling (Borck and Brueckner, 2016; Creutzig, 2014). Unit taxes on land and/or taxing building envelopes are important complements for incentivizing efficient building design (Borck and Brueckner, 2016), and to provide for equitable distribution of high urban land rents (George, 1879).

To respect that every city is different and requires place-specific action, but also to still provide information relevant for global pathways, typologies of cities provide a useful tool bridging this gap (Baiocchi et al., 2015; Creutzig et al., 2015), Figure 3.16). Such typologies could be leveraged by a) hybridizing them with systematic literature reviews of cities and policy solutions (Lamb et al., 2018); and b) by combining them with big data approaches in the analysis of human settlements (Creutzig et al., 2018a).

As an illustration, let us consider three types of cities. First, we take the low-density human settlements like Edmonton, Canada. Here, available space offers the low-cost construction of above-ground rail-based transit. Sub-urban environments can be connected with shared automated, electric vehicles. New housing will focus on high-rises around public transit stations, making the best use of abundant woody resources.

Second, we consider Nairobi, a city based on walking and matatu-minibusses, creating congestion while providing little additional mobility. Bus rapid transit systems or tramways are the option of choice to create higher volume transit also to the new sub-urban settlements. This requires overcoming the political economy of matatu business owners and providing new jobs. The example of Addis Ababa demonstrates the possibility of this approach. Housing efforts will focus on slum upgrading and providing new settlements along transit lines.

Third, we consider Beijing, which has built a world-class subway system but at the same is stuck in tremendous congestion.



Count	5	6	5	24	6	36	127	14
Energy pc GJ/pop	64	67	21	76	201	103	106	148
GDP pc USD/pop	5,200	7,200	3,200	7,200	25,900	28,300	31,750	31,100
Gasoline Price USD/l	0.9	1.0	1.1	1.0	0.8	0.9	1.4	1.4
Pop Density pop/km²	214	190	4,600	1,400	260	3,400	1,500	1,600
$HDD_{15.5\,°C}$	720	3,760	30	1,560	1,640	1,520	2,120	3,530

Figure 3.16. An urban typology with respect to drivers of energy use, classifying 225 representative cities into eight types. Similar typologies, organized around policy measures and SDG pathways, will help to bridge the gap between urban-specific solutions and global pathways. Source: Creutzig et al. (2015).

Flexible bike-sharing offers a way forward to increase access to the subway network(Wu and Xue, 2017). However, to combat congestion and air pollution high congestion charges will be needed (Creutzig and He, 2009). Policy-centric design and a fostering of less central cities, as already attempted with the high-speed-railway network will further serve preventing high pollution impact in dense urban environments. The greening of cities is seen as crucial to mitigate urban heat island effects (Weng and Yang, 2004).

3.4 Research needs

In the previous section, we discussed how different analytical approaches and model-based pathways provide information on achieving specific SDGs and longer-term sustainability by 2050. However, the question on how to achieve the full set of SDGs requires further accounting for the interlinkages across various domains. While IAMs and the scenarios developed by and for these models have contributed to providing more integrated perspectives on domains such as energy, food, water security, biodiversity and air pollution, they would need to be further developed to widen their applicability, in terms of sectors, spatial coverage and detail (van Soest et al., in review; Zimm et al., 2018). Advances in individual disciplines (e.g., health, demography, urbanization, governance, and digitalization) and interdisciplinary research on how to integrate this knowledge in IAMs and their analyses are needed. On the way to SDPs, a range of different approaches may be undertaken that address the limitations of currently available tools and analyses. These research needs can be grouped into two broad categories: 1) IAM development, and 2) collaboration with other disciplines. These are discussed in further detail below.

3.4.1 IAM development

A key priority is further development of IAMs towards a more holistic analysis of SDPs. While IAMs were originally developed to analyze climate change mitigation strategies, adopting them for the analysis of SDGs and longer-term SDPs requires advances in several areas. We summarize those advances in a set of research priorities for the use of IAMs in sustainable development analysis:

Increasing coverage of SDG interactions

Van Soest et al. (in review) provide an overview of key linkages across SDGs and experts' assessment of which individual SDGs and which linkages are currently covered by the models, and which would be covered in the near future based on planned model developments. This analysis shows that a few SDGs are not well captured by IAMs (Figure 3.17), foremost the human development and social goals on education (SDG 4), gender (SDG 5), inequalities (SDG 10), and peace and governance (SDG 16), and partly also cities (SDG 11) and oceans (SDG 14) (van Soest et al., in review). Some of these SDGs and related linkages are, however, reflected in upcoming model advances. Areas researchers are working on include the poverty-hunger-health nexus, interlinkages between health and clean water and inequalities, and between (energy) poverty and climate. Further down the road, potential coverage could include the effects of poverty on health and economy, of education on inequalities, renewables on cities, climate mitigation on the oceans, and of cities on water, economy, governance and infrastructure. Many other interactions and areas identified by experts for model development are related to poverty (linkages with access to education, health care, clean energy and water, nutritional food), health (linkages with food, air pollution, clean water, energy, climate change, life below water and on land), industry, innovation and infrastructure (cutting across cities, buildings, public transport, digitalization and automation, technological progress, and governance), education and inequalities (linkages to gender equality, health, poverty, consumption patterns, access to resources, peace and governance), and consumption and production patterns (linkages to climate, land, oceans and resource access).

Using models within a consistent framework

IAMs can cover more SDG dimensions and interactions than they currently do, but they will not be able to include everything, also because fully endogenizing all SDGs is neither feasible nor desired. This requires the adoption of a carefully tailored scenario and soft links approach, which allows to explore the synergies and trade-offs within and between SDPs in a systematic way. Furthermore, the diversity of IAMs should be reflected in their application, considering each IAM's strengths and intended application. For example, the integration of IAMs with sectoral bottom-up models could be enhanced. Enhancing feedbacks and links between models and other tools, including through a consistent framework such as put forward by TWI2050, are options for improvement (van Soest et al., in review; Zimm et al., 2018). Such a framework could be based on a structural assessment of the input assumptions and key equations, clarifying how IAMs differ in modeling SDG interactions.

Better integration of SDG indicators

Another way forward towards improving the representation of relevant SDG indicators is to move beyond the status of "output" indicators (i.e. only one-way relationships, quantifying first-order impacts) towards a more dynamic integration including

Figure 3.17. IAM representation of SDGs. Colors represent average score for individual target coverage based on a survey among IAM models. Green: SDG is well captured and most targets can be modeled (darkest green: average score above 3, green: average score between 2 and 3, light green: average score between 1.5 and 2). Orange: SDG can partly be quantified (not all targets or only proxy indicators), with average scores between 1 and 1.5. Red: SDG is not well captured, with average scores below 1. Source: adapted from van Soest et al. (in review).

feedback effects. This is especially relevant for policy solutions that are assessed by IAMs. In addition, a more detailed representation of policy instruments is required for 1) analyzing the effect of specific policies that are (proposed to be) implemented on the ground on other SDG domains, and 2) contributing to the design of smart policy packages that avoid trade-offs, and where possible even enhance synergies. To get a full picture of the synergies of and trade-offs from policy options, IAMs should aim to advance the representation of relevant processes and dynamics across SDGs. This can include, for example, better representation of distributional aspects of socioeconomic dynamics and better mapping of non-technological strategies in IAMs, and is also relevant for the degree of detail of how policy instruments are reflected in the models (e.g., climate policy being often represented by a carbon tax). Ongoing model development is currently aiming at allowing the testing of various sets of policy instruments to help design smart policy packages that avoid trade-offs (Bertram et al., 2018). To this end, improving transparency of databases and assumptions of models will be essential.

Better representation of geographies and actors

SDGs cut across a range of geographical scales, from local to national to global (Bijl et al., 2018; Weitz et al., 2018; Allen et al., 2016). While most IAMs are able to cover different scales, such as the national level, for a certain set of SDG aspects, increasing their spatial resolution would be one way to increase the usefulness of their assessments to policymakers. This will have to happen with feedbacks to the regional or global level in mind. Including heterogeneity in modeling explicitly in order to reflect the distributional dimensions of many SDGs is also required. This can relate to geographic scale, such as differentiating between urban and rural households, but also to cultural, religious or socioeconomic groups, all relevant for targeted policymaking. However, improving actor heterogeneity and geographical resolution is subject to availability of data as well as to capacity of modeling approaches. Another way forward is to improve interactions across models representing different resolutions, both in terms of space (e.g., global and national or local level) as well as actor heterogeneity (e.g., different household types, private sector, governments). This will allow for higher spatial and actor-based resolution of the analysis, making models more useful for national policymaking during the implementation process (Gao and Bryan, 2017; Allen et al., 2016). TWI2050 has already initiated work on bringing in regional perspectives and diverse stakeholders to improve pathway development (Box 3.9).

3.4.2 Collaboration with other disciplines

Many of the identified limitations cannot be addressed by IAMs alone. The underlying assumptions, granularity of available data or the analysis of results require IAMs to draw on insights from other disciplines or to develop new tools jointly with other scientific communities. As the 17 SDGs cover many scientific fields, providing research needs for all these domains would be beyond the scope of this report. We focus here on select research needs conceivable to be relevant for IAMs in the foreseeable future and related to trends dealt with in this chapter.

Linking scientific communities and developing integrated pathways within a consistent framework

Many interactions, deemed important by experts, are not currently covered by IAMs, and in some cases they are also not considered to be fully quantifiable in the foreseeable future (van Soest et al., in review). Knowledge gaps lie in interactions across the human development goals, where research could aim to identify and test the causal links. This relates mainly to human development interactions and governance, institutions and existence of legal frameworks and policies (Allen et al., 2016) and their effects on many other SDGs: the effect of poverty on education, of education on economy, of gender equality on inequalities, and of peace on international cooperation. These could be covered differently than through model advances, foremost e.g., by linking scientific communities and combining models. Such an approach would be beneficial especially for the

Box 3.9. Bringing regional perspectives to TWI2050 – The African Dialogues.

Highlighting the regional perspectives in SDPs will be key to foster the transformation processes at multiple levels. Therefore, an important branch of activities in the TWI2050 consortium focuses on cross-scale questions including the regional perspectives and cross-scale relationships. This is also illustrated by the different trends in land use in two alternative sustainability-oriented scenarios: i.e. the SSP1 baseline and the derived mitigation scenario consistent with the 1.5°C climate target (Doelman et al., 2018; Rogelj et al., 2018; van Vuuren et al., 2017) (Figure 3.18). Similar differences in regional land use also play a role other sustainability scenarios.

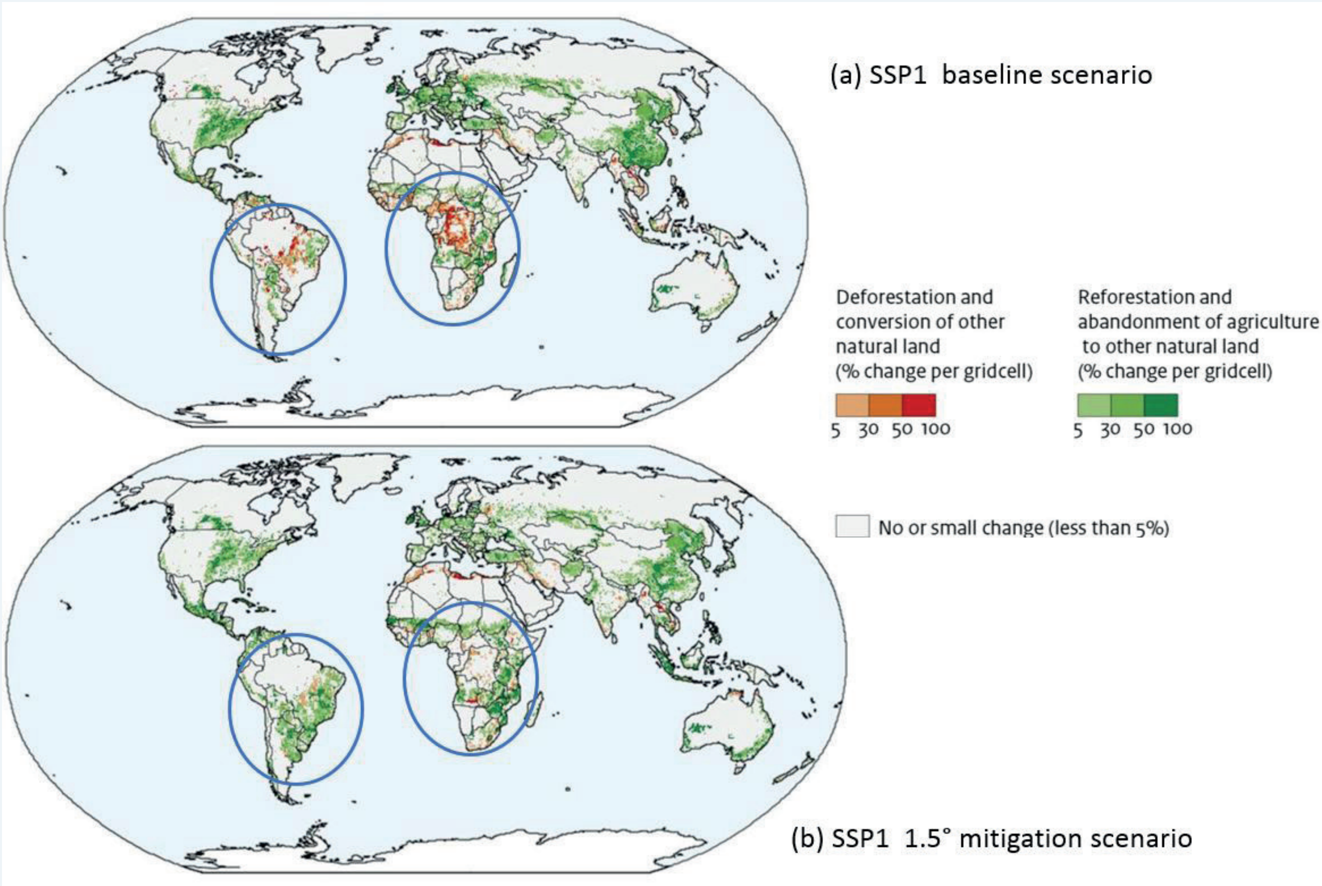


Figure 3.18. Change in land use (percentages of grid cells) between 2010 and 2100; deforestation and conversion of other natural land to agriculture (red) and reforestation and abandonment of agriculture to other natural land (green) for SSP1 baseline scenario and SSP1 1.5 °C mitigation scenarios (1.9 W/m^2). The circles emphasize the contrasting resulting land use patterns for Latin America and Africa. In SSP1, the premise is that livestock sector intensifies substantially, and food losses and dietary preferences for animal products are reduced, leading to abandonment of grazing land. Abandonment takes place in relatively productive areas (predominantly north-western Brazil, for instance) leading to high potential for bioenergy production. In sub-Saharan Africa, SSP1 shows a decrease of grazing land, though cropland is still expanding. When considering additional mitigation measures (b), the amount of deforestation in the Brazilian Cerrado and sub-Saharan Africa reduces significantly, with a considerable increase of forest areas. REDD together with reforestation of degraded forest areas leads to substantial increases in forest area in the mitigation scenarios. However, in Africa, in the mitigation scenario, agricultural demand cannot be fulfilled within the region, requiring high levels of net import from other regions. Source: Doelman et al (2018).

In the coming years, it is foreseen that multiple SDPs will be created in the scope of TWI2050, also presenting regional differences, representing different regional branching points, trade-offs, policy options and – not less important - premises related to the regional developments. A good illustration is the first regional stakeholder workshop of the TWI2050 process, which was held in 2017 in close collaboration with SwedBio and the SDG Centre for Africa in Kigali, Rwanda. The focus of the 1st Dialog Workshop was on how agriculture in Africa can contribute to meeting the SDGs within the planetary boundaries. The Dialog brought together a diverse group of stakeholders to explore SDPs and add different African perspectives. The event was organized around clusters of SDGs. Figure 3.19 presents a schematic overview of the core pathway elements discussed during the event, synthesized around governance and agricultural practices issues. The long-term vision is to refine the process of building regional pathways, using them to enrich the global pathways, while also promoting the cross-scale discussion about SDG implementation in subsequent workshops. Those will, for instance, use a structured multi-scale, participatory scenario process (Rosa et al., 2017; Folhes et al., 2015; Oteros-Rozas et al., 2015) to create and integrate pathways according to the TWI2050 framework. We intend this to be the seed for many other similar activities to be replicated in other contexts.

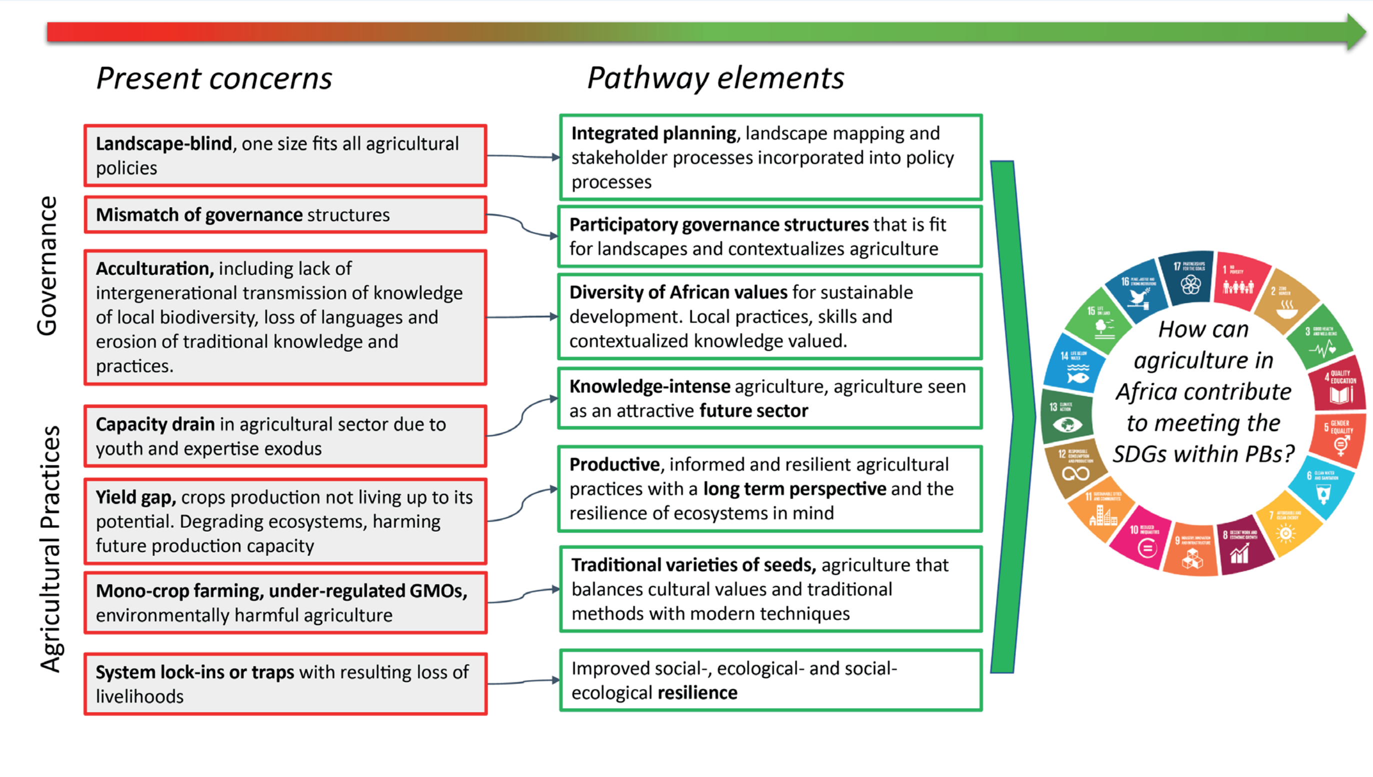


Figure 3.19. Messages from the discussions of the African Dialog include that SDPs must acknowledge the multiple roles, functions and impacts of agriculture for social-ecological resilience and wellbeing. Africa's agricultural landscapes and food systems have been shaped and sustained by deep social, traditional and cultural values. African cultural values for food and agriculture need reviving in many places and need recognition and protection in policy. Furthermore, participants argued that rural and agricultural livelihoods need to be seen as attractive. The current waves of urbanization compound the problems of degradation of natural resources and fragmentation of rural communities. The view that only cities provide opportunities is particularly prevalent among the youth, driving a sector-specific brain drain that harms the sustainability and effectiveness of the agricultural sector at large. Incentives and policies to retain youth and increase women's participation in agribusiness may counteract this trend. The complete workshop report is available at: https://swed.bio/reports/report/dialogue-workshop-report-afri-can-dialogue-twi2050/. Source: Collste et al. (in preparation).

social and institutional areas (e.g., demography, governance, and poverty research) (van Soest et al., in review; Zimm et al., 2018).

More integrated pathways with contributions from a variety of scientific communities could be brought together by a joint narrative and harmonized exogenous assumptions, similar to the SSPs (O'Neill et al., 2017; Riahi et al., 2017). Zimm et al. (2018) provide an overview of knowledge gaps (e.g., on gender, oceans or governance) within the SSPs vis-à-vis the SDGs that call for collaboration across scientific fields. They call for further development of the SSP narrative and quantifications to encompass SDG dimensions currently not considered, on a way to a more comprehensive framework. Already today, the SSPs enable researchers from different scientific disciplines to base their work on consistent assumptions and to adapt them to their specific needs and methods (e.g., Hegre et al. (2016)), telling a joint story. This kind of research approach needs to be broadened to inform policymakers working on SDG implementation. It also leads to cross-fertilization between research communities, especially social and natural sciences. These communities need to develop a common understanding and language to be able to work together and find solutions for the grand challenges the SDGs aim to overcome. The TWI2050 framework aims to provide such a bridging function, and the interdisciplinary CD-LINKS[4], PATHWAYS[5] and REINVENT[6] projects provide further examples of developing a common understanding.

Reflecting societal change and governance better

IAMs apply a number of concepts, including narratives, pathways, policy assumptions, etc. which so far largely use ad hoc assumptions on societal change and governance. Thorough theory-based assumptions that underpin causal relationships between societal change and governance on the one side and sustainable development on the other are only now emerging (Chapter 5). These concepts provide entry points for social science knowledge, which can enrich modeling efforts in various ways: i) insights on the use and function of narratives in societies, ii) insights on (drivers of) value changes in societies, iii) insights on (drivers of) changes of political systems and orders, iv) insights on (drivers of) policy change and diffusion, v) insights on the adoption rates of certain technologies, vi) a review of current suggestions and potentially further development of indicators for measuring SDGs 16 and 17, vii) an indicator and data set on country implementation capacities at a global scale, viii) country case studies on the political economy of policy/nexus/SDG implementation. Social science research is also relevant when it comes to the implementability and acceptability of policies(Devine-Wright et al., 2017). Empirical analyses will also be needed for concrete policy advice at local and national level (van Soest et al., in review).

Application of demographic tools in the field of global environmental change

Despite a close link between population and sustainability, demography remains under-represented in global change research. Historical development of the field of population and environment since the 1960s in which the Malthusian 'limits to growth' was dominant carries bitter controversies regarding family planning and reproductive rights. This makes many contemporary demographers shy away from the topic of environmental change (McDonald, 2016). However, demography has relevant theoretical concepts and methodological tools that can be useful in sustainability research. This includes, for instance, population estimates and projections and the study of differential vulnerability (Muttarak et al., 2015). In particular, the potential in forecasting can contribute to the understanding of how the world will look like under different socioeconomic development scenarios (Lutz and Muttarak, 2017). More application of demographic tools in the field of global change and sustainable development thus is needed. In particular, taking account of heterogeneous characteristics of the population and their spatial distribution is crucial for policy planning since consumption patterns and vulnerability vary with population characteristics (Lutz and Striessnig, 2015). Recent population projections by IIASA researchers, for example, have introduced education and labor force participation in addition to age and sex to describe population heterogeneities (Lutz et al., 2018; Lutz et al., 2017; Loichinger, 2015). These population characteristics matter not only for demography but also for a societies' adaptive capacity, economic growth, governance and the like (Lutz and Muttarak, 2017; Muttarak and Lutz, 2014; Lutz et al., 2010; Lutz et al., 2008).

Education as a means for achieving other SDGs

Education is commonly treated as an end, a goal in the sustainable development agenda. However, recently it has been argued that education is also a means through which other goals are to be met (Bengtsson et al., 2018). In the context of health, for instance, a recent study empirically shows that it was an increase in mean years of schooling that explains an increase in life expectancy globally, and not income as presented in early literature (Lutz and Kebede, 2018). Similarly, in the field of vulnerability, the level of education is found to be a better predictor of disaster mortality in a country than GDP (Striessnig et al., 2013). Research of this kind is needed, especially because it can inform policymakers which area of sustainable development to prioritize.

Advancing health research and global change

The complex interactions and feedbacks between health, development, and drivers of global change remain largely unexplored. Better understanding of these feedbacks could provide insights into facilitating transformations to achieve the SDGs and future health goals. A comprehensive health research agenda would emphasize first and foremost a vision of system transformation in light of global changes. Thus, cross-disciplinary collaborations between health experts and those in other sectors are needed to better understand likely feedbacks between health and other systems, which could further inform existing narratives around health systems under global change with regards to the level and timing of investments to protect and promote health in a future that will differ significantly from today (Sellers and Ebi, 2018). Once feedbacks between health and other sectors are better understood, then they could be incorporated into IAMs to quantify their spatial and temporal variability as well as likely magnitude.

Pushing urbanization research

Key research gaps in urbanization research are the development of structured scenarios that quantitatively and qualitatively characterize sustainability implications of different choices made. The specific goals of SDG 11 have not yet been explored quantitatively and with respect to development in 2030 or 2050. One reason is that the urban/housing/mobility community emphasizes the problematic situation in specific cities but hesitates to generalize patterns and dynamics across cities. Another reason is that issues like adequate housing have been not consistently defined and may subjectively vary between different cities. Top-down scenarios in turn might not be very informative as they lack detail. A transdisciplinary approach would be very helpful to push the agenda[7].

[4] http://www.cd-links.org/

[5] http://www.pathways-project.eu/

[6] https://www.reinvent-project.eu/

[7] The IPCC secretariat is currently consolidating a research agenda on urbanization, cities and climate change: https://citiesipcc.org/beyond/conference-outputs/

Developing an integrated understanding of demand

Using consumption and demand as an entry point (3.3.1) to different systems opens up a diverse research area which on the one hand, calls for individual disciplines (such as anthropology, sociology, psychology, economics, engineering) to deepen their knowledge on the underlying drivers (Creutzig et al., 2018b)A synthesis of research on cultural norms and values, socio-demographics, habits, preferences and structural aspects of consumption and consumption patterns is essential. On the other hand, bringing together the scientific knowledge of these diverse disciplines to jointly work on an integrated assessment of demand for services and products and their potential environmental impacts (e.g., carbon or material footprint) will push the scientific frontier. Interdisciplinary and transdisciplinary research will improve modeling human decisions, and further approaches treating humans as agents.

In addition, research on policy options that influence demand and its socioeconomic and environmental impacts is needed; on question of: which measures are effective, socially and politically acceptable, and under which conditions can they be implemented? Combining theories on behavioral tipping points, social norms, transition theory, and insights from bottom-up assessment of techno-economic studies and models with IAMs will be one way forward, reflecting interactions between sectors and systems. For more consistent and systematic modeling efforts, it is important to be able to access and compare grounded assumptions on demand. A common interdisciplinary framework such as put forth by TWI2050 can help systematize such assumptions and how they are reflected in models, fostering cross-sectoral learning.

Improving the representation of labor markets, innovation and inequality

Macro-economic modeling frameworks capturing the interaction between technological progress, frictional labor markets and distributional implications for household income are actively researched, and a better understanding is needed which of these frameworks are mature and computationally efficient enough to be adopted by large-scale numerical modeling with IAMs. A huge force in shaping future innovation, employment, and inequality will be the digital revolution and the associated automation of cognitive tasks. Collaboration between the macro-economics, machine learning and sustainability research communities is needed to assess the opportunities and threats of these developments for a sustainability transformation.

All the above research needs address elements that will enhance the evidence-base guiding the implementation of the SDGs, provided that the scientific community can convey its knowledge to national decision makers on policy choices and actions, strengthening the national science-policy interface (Colglazier, 2018). For this to happen, governments and institutions at all levels need to prepare for these advances and actively promote and support the scientific community.

4 Governing the Transformations Towards Sustainability

Julia Leininger, Ines Dombrowsky, Dirk Messner, Anita Breuer, Constantin Ruhe, Hannah Janetschek, Hermann Lotze-Campen

Key Messages

1. **Peace and good governance are uncontested preconditions for sustainable human development.** However, neither peace nor good governance is sufficient for achieving the six Transformations Towards Sustainability. Good policies, change of social values and a reformed culture of global cooperation are as relevant.
2. **Inclusive institutions are crucial in bringing about egalitarian societies, which have been demonstrated to perform better in promoting innovation, prosperity and wellbeing.**
3. **Transformations to sustainability require governing interlinkages between Sustainable Development Goals (SDGs).** This implies adaptive polycentric multi-sector, multi-level, multi-scale and multi-actor governance approaches, even though they may be hindered by veto players, power asymmetries, transaction costs and low capacities.
4. **Transformations to sustainability are likely to be disruptive and, thus, could even trigger violent conflict.** In history, most great transformations have been accompanied by violent conflict, including wars. Acknowledging governance reforms to govern social change as a vital part of pathways to transformation is thus crucial.
5. **Many of our societies are now at a tipping point where they can step up the pace of transition towards implementing the 2030 Agenda and the Paris Agreement.** This tipping point situation is characterized by three major bifurcations: The transformation towards sustainability, nationalist counter-transformations and the far-reaching dynamics of the digital transformation.

4.1 Introduction

The six transformations to sustainability are different from previous transformations – they differ with regard to scale, time, space and connectedness with each other. Getting governance and the economics as well as social change right is fundamental for achieving these transformations. While the previous chapters focused on the necessary content of sustainability policies and the social, environmental as well as economic trends, this chapter addresses the political and institutional points of departure of the six transformations. It focuses on governance in nation states because states are still the center of binding, political decision-making. However, to make the six transformations happen, transformative governance is needed from the local to the global level. For instance, governance needs to be flexible enough to accommodate state and non-state actors from different sectors and global governance still must be stronger for addressing inter- and transnational problems effectively. Elements of transformative governance as well as economic principles will be addressed cursorily in this chapter and they will build the basis for future research of TWI2050.

The 2030 Agenda also acknowledges governance on all levels as a goal in itself and as an enabler of the Sustainable Development Goals (SDG) implementation (especially SDGs 16 and 17). This chapter starts with a mapping of governance and state capacities all around the world and assesses its implications for the transformations to sustainability (Section 4.2.1). Then it turns to violent conflicts and state fragility as structural impediments for achieving the SDGs (Section 4.2.2). Departing from these preconditions, the chapter presents what we know about integrated implementation of sustainability policies and, more particular, how to govern the interlinkages during implementation (Section 4.3). General principles for governance and financing the SDGs as well as solving political problems (politics) are addressed. The chapter concludes with a description of the global context of the six transformations to sustainability. It acknowledges three bifurcations on the way to sustainability and gives a direction towards sustainability (Section 4.4).

4.2 Enabling political and societal conditions for the transformations to sustainability

Peace and good governance are uncontested preconditions for sustainable human development (Fukuyama, 2016; Boutros-Ghali, 1992; World Bank, 1992). However, neither peace nor good governance are sufficient for achieving the six Transformations Towards Sustainability. While there are a number of countries that need to improve the capacity and performance of political institutions to achieve sustainable development, there are others, which are well governed and stable but fail to meet the SDGs or even obstruct their achievement globally. For instance, least developed countries need to enhance their governance capabilities to be able to improve food security and waste management. OECD countries, on the other hand, neither meet certain goals, nor foster their achievement such as the reduction of CO_2 emissions because neither their economic priorities and climate policies nor the consumption preferences of their populations have prioritized sustainability. In other words, OECD countries have the capabilities to change towards sustainability but need to get their policies right. Creating a collective culture of sustainability[1] requires that states promote behavioral and ethical norms that change the values, actions, and attitudes of political elites, the private sector, civil society and people at large. Developing countries face larger challenges because missing capabilities and institutions need to be built simultaneously with the right policies and attitudinal changes (World Bank, 2017; Acemoglu and Robinson, 2012).

Peace and stability are decisive factors for development. The relationship between peace and development is often described as a sequence. First stability and peace, then development. However, for building scenarios for 2050 the reversed causality of this relationship is as important. Transformations to sustainability are likely to be disruptive and, thus, could even trigger violent conflict. In history, most great transformations were accompanied by violent conflict, including war (Osterhammel, 2009). Although a peaceful transformation to sustainability is the role model for the 2030 Agenda as TWI2050 we need to consider scenarios, which take into account potential outbreaks of conflictive dynamics.

4.2.1 Governance and state capacities

A capable state[2], which is able to meet the challenges of complex governance modes, is an important prerequisite for peaceful transformations to sustainability. Strong political institutions are crucial but they will only be effective for an integrated implementation of the Agenda 2030 if they are able to accommodate the disperse distribution of power, multiple centers of authority and competitive relationships that characterize policymaking between the state, market and society in a multi-polar world (Fukuyama, 2004). This holds true for countries in the OECD and developing regions.

Whether democratic regimes are better suited to foster sustainable development than autocratic regimes is an ongoing debate. Empirical studies yield mixed results, which suggest that democracies do not outperform autocracies with regard to development results, for instance, the provision of public goods such as education or clean water and climate-friendly policies (Stepping and Banholzer, 2017). However, democracies do better in providing security, internal peace and protecting the individual rights of their citizens than autocracies (Stoker, 2017; Faust, 2007). Given these mixed results of specific regime types, this chapter focuses on specific characteristics of political institutions, state capacity and governance for implementing the 2030 Agenda. Before getting closer into the characteristics of political institutions and governance modes we first focus on political macro-structures. Despite polycentric dynamics, the state is still a central entity for governing individual societies,

Box 4.1. From good governance to inclusive governance.

Good governance is not the only game in town anymore. In international development debates, we are currently observing a shift away from good governance to the notion of "inclusive governance". Although good governance is still widely used to assess the quality of governance processes and government performance (the keywords being accountability, transparency, efficiency, government responsiveness, effectiveness), practitioners and scholars criticize the hitherto prevailing concept of good governance because it does not capture all attributes that are necessary to build equal societies in which no one is left behind. While good governance implies effective government for sustainable development outcomes, recent studies address the need to include the distribution of policy outcomes. In this sense, political institutions must be inclusive and able to redistribute public goods and foster equality between the people (Acemoglu and Robinson, 2012). In its recent World Development Report "Governance and the Law", the World Bank emphasizes that the distribution of political power drives institution-building and the distribution of policy outcomes (World Bank, 2017). The Bank concludes that building capacities is important but not sufficient unless power constellations are taken into account.

By adopting SDG 16 on peace, justice and strong institutions and SDG 10 on equality, as well as the guiding principle of "leave no one behind", the 2030 Agenda responds to these debates and to a critical gap identified over the process of MDG implementation. This strong emphasis placed on the achievement of peaceful societies, general reduction of violence, inclusion and social justice through adequate governance constitutes a veritable shift in the global development agenda. Although the importance of good governance was cursorily mentioned in the Millennium Declaration, no specific MDG was developed to focus attention and resources on governance issues, let alone the question of political inclusion. By contrast, there is now a broad consensus that the governance targets under SDG 16 are not merely desirable development outcomes, but need to be understood as indispensable enablers for achieving all other goals (e.g. Sachs, 2015). Although there is a common agreement amongst states about the need to properly governing the SDGs (Kanie and Biermann, 2017), the concept of governance is still contested and more time will be needed to see whether the notion of inclusive governance will effectively replace the current concept of good governance.

[1] See also Section 4.3.

[2] Although state capacity is not explicitly mentioned in SDG 16 it highlights a related concept, namely effective and transparent institutions (SDG target 16.6).

global affairs and for regulating markets. If states turn fragile, they face serious governance problems, which inhibit effective policymaking for sustainable development (World Bank, 2017). On the other hand, if states turn too strong, they are more likely to concentrate power and limit the freedoms of their people.

State fragility recurs in different patterns. Different types of state fragility have different implications for state performance. We use the "Constellations of State Fragility", developed by the German Development Institute, to describe the implications for meeting the SDGs (Grävingholt et al., 2018). The literature on state fragility identifies a number of dimensions of fragility, which describe the core functions of the state (Grävingholt et al., 2015; Call, 2011; Carment et al., 2010). We distinguish three core dimensions of state functions (and, by implication, of fragility): state authority (i.e., the ability to uphold the state monopoly of violence); state capacity (the ability to deliver basic services to the population); and state legitimacy (the general acceptance by the citizenry of the state institutions' claim to set and implement binding rules) (Grävingholt et al., 2015). Each dimension refers to a specific constellation of state-society relation. Differentiating and measuring these three dimensions enables to identify six clusters of states, whereby each cluster displays distinct statehood qualities or deficiencies. The six clusters thus represent empirically observable constellations of state fragility (see Table 4 .1).

The world map of most likely constellations of state fragility shows how the macro-political starting points for implementing the Agenda 2030 vary across regions (Figure 4 .1). Dysfunctional states located in Africa and Asia face complex problems and war, which requires state-building and renewing the contract between state and society. Achieving peace and stability (SDG 16) is certainly the most important objective in these countries, where 3.6% of the world population live. Although small in total numbers, dysfunctional states can destabilize entire regions and increase instability in neighboring countries (Stewart, 2006). In case of countries with low capacities, the likeliness of destabilization and violent conflict due to external shocks such as floods is higher than in more capable states. More than one third of the world population lives in these countries (37%). For instance, if the Malian state would have had capable institutions to govern its whole territory before 2012, the inflow of weapons and militias from Libya would not have been as likely to destabilize a whole country. Low capacity is thus not only a threat to service delivery and policy implementation but also to security and stability in a country (Asadullah and Savoia, 2018; Yanguas, 2017; Bukena and Yanguas, 2013). In turn, states with low levels of authority but better capacity and legitimacy struggle with localized conflict and high numbers of crime (e.g., Brazil, El Salvador or South Africa). They are able to provide basic services to their populations and implement development policies effectively (to around 7% of the world population). However, low authority will hinder efficient and full SDG implementation because it is often correlated with high levels of corruption and mismanagement (Fukuyama, 2018). Low legitimacy states are marked with a weak or mediocre relationship between citizens and state. They might perform well in service delivery but are not able to provide a societal environment free of fear and distrust. Around 35% of the world population live in these states. Semi-functional states have good preconditions for improving their situation (around

Table 4.1. Description of constellations of state fragility. Source: For more information on theory, methodology and measurement see Grävingholt et al. (2018) available at www.statefragility.info.

Observable constellations	Qualitative description
DYSFUNCTIONAL STATES	States in this cluster have very low scores on all dimensions of statehood. These states usually have very limited authority over the use of physical violence, have little capacity to provide basic public services and score low on legitimacy.
LOW AUTHORITY STATES	States in this cluster have very limited authority over the use of physical violence, but have the capacity to provide some basic public services and have medium scores on legitimacy.
LOW-CAPACITY STATES	States in this cluster display little capacity to provide basic public services, but they have decent authority over the use of physical violence and usually have mediocre scores on legitimacy.
LOW-LEGITIMACY STATES	States in this cluster have low to mediocre scores of legitimacy, but usually have decent authority over the use of physical violence and the capacity to provide some basic public services.
SEMI-FUNCTIONAL STATES	States in this cluster have medium scores on all dimensions of statehood. These states usually have decent authority over the use of physical violence, possess the capacity to provide some basic public services and score better than average on legitimacy.
WELL-FUNCTIONING STATES	States in this cluster display very good scores on all dimensions of statehood. These states usually have the authority over the use of physical violence, possess the capacity to comprehensively provide basic public services and score high on legitimacy. They are not considered as "fragile".

6% of world population). However, semi-functional and well-functioning states have in common the fact despite a generally good predisposition, vested interests, power asymmetries and competitive relationships between central players can hinder the implementation of the SDGs (affecting 11% of world population in well-functioning states). In these cases, SDG implementation is more a question of the ability and political will to reform political institutions and incentivize collective action for a global common good.

and regulations as well as the right mandates and policies for public institutions (Asadullah and Savoia, 2018; Acemoglu and Robinson, 2008)

Transparency and accountability (as outlined in SDG target 16.6) are mutually dependent elements of governance, which are of enormous importance for delivering the SDGs. Ensuring that governments are honoring their commitments to the 2030 Agenda is only possible when adequate mechanisms for monitoring progress are in place. For example, knowing

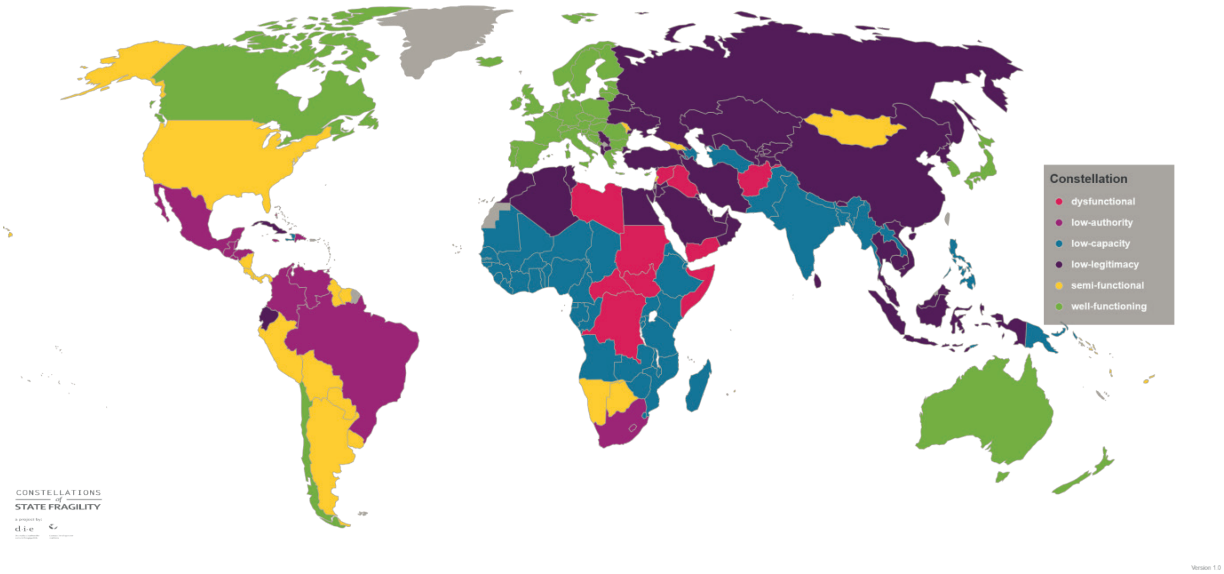


Figure 4.1. Constellations of state fragility worldwide (2015). See description of constellations in Table 4 .1. Source: Grävingholt et al. (2018)

All types of fragility have in common that they result from governance deficiencies. In order to overcome fragility, institutions need to be transformed. The notion of effective institutions is closely related to the concept of state capacity. Development literature formerly strongly focused on the effects of state capacity on economic development. More recently, there has been growing evidence and scholarly agreement that capable state institutions are key to the delivery of public services and consequently critically affect other development outcomes such as poverty and inequality (Asadullah and Savoia, 2018; Denney et al., 2017; Savoia and Sen, 2015; OECD, 2014; Petersen and Engberg-Pedersen, 2013). Institutional effectiveness - i.e., the degree to which institutions are able to meet their assigned missions and achieve their intended outcomes - is hence an important requirement if states are to fulfill their mandates of administrating public affairs and providing basic goods and services. However, state capacity cannot be measured exclusively by the outputs and outcomes that a state produces (e.g. Fukuyama, 2014; Holt and Manning, 2014). Instead, the ability of institutions to produce these outcomes should be a function of inputs, such as establishing a common-good oriented culture for public servants, adequate financing, staffing, and training, as well as procedures; i.e., the design and enforcement of the rules and regulations that these institutions have to adhere to. The improvement of development outcomes therefore critically hinges on improving these rules

whether the commitment to the principle "leave no one behind" is being adequately funded, is impossible in the absence of transparency about the resources dedicated to each of the SDGs and the disclosure of data disaggregated by disability, gender and age. However, holding governments and their institutions to account for deviating from their commitments requires the existence of effective sanction mechanisms. Effective accountability hence both involves the obligation of public officials to inform about and explain their actions, as well as the capacity of citizens and accounting agencies to punish those in power if they violate their public duties (e.g., Behn, 2001; Schedler, 1999). The absence of effective accountability opens the floodgates to clientelism and corruption (Rose-Ackerman, 2006; Lederman et al., 2005; Strom et al., 2003; Ferejohn, 1999; Rose-Ackerman, 1999; O'Donnell, 1998), both of which facilitate the abuse of public office for private gain. Clientelism, in addition to directing public resources towards specific client groups, distorts political competition and undermines the optimal allocation of public goods and services (Fox, 1994). Corruption, in addition to enriching individual public servants, distorts markets and compromises service delivery (Rose-Ackerman, 1999). This has serious implications since it diverts resources that are needed to meet sustainable development goals. The worldwide cost of corruption alone is estimated at 2 to 5% of global GDP per year (European Parliament's Committee on Development, 2015; OECD, 2015).

Figure 4.2 shows the global average development of accountability from 1900-2016 using the Varieties of Democracies Accountability Index. The index measures three dimensions of accountability: vertical accountability, i.e., the ability of citizens to hold their governments accountable through elections and political parties; horizontal accountability, i.e., the capacity of state institutions such as legislatures and the judiciary to oversee the government; diagonal (or social) accountability, i.e., the oversight executed by civil society and media (Mechkova et al., 2018). Values run from -2 (total absence of accountability) to 2 (full accountability).

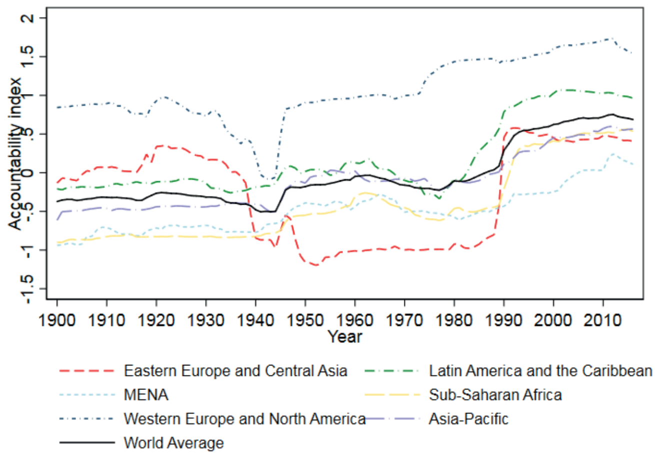


Figure 4.2. Accountability, global and regional trends, 1900–2016. Source: Coppedge et al. (2016).

As can be seen from Figure 4.2, since the beginning of the 20th century three phases of accountability development worldwide can be distinguished, which concur with the three waves of democratization (Diamond, 1996; Huntington, 1991). Starting from low levels at the beginning of the 20st century, average accountability further declines during the 1930s and 1940s. Following World War II, the global average of accountability rises above pre-war levels and finally experiences a steep rise following the disintegration of the Soviet Union. However, it stagnated and did not contribute to further global spread and deepening of democracy in the 2000s. In sum, we can observe a positive global trend towards more accountability in a historic perspective. Although this implies a trend towards achieving SDG 16 (target 16.6), it does not necessarily mean that more accountability on a globally averaged level facilitates the implementation of the other SDGs. There are two caveats. First, individual countries and regions perform differently with regard to accountability. Second, policy content matters for judging whether more accountability leads to better policies for the transformations to sustainability. For instance, governments might be held accountable on many policy issues. But as long as there are no proper policies that lead to more sustainability, accountability does not contribute to the transformations to sustainability.

Inclusive institutions are key in bringing about more egalitarian societies (SDG targets 10.2 and 16.6). They ensure equal protection of rights, provide equal access to power, and facilitate equal access to resources and services. Inclusive institutions thus ensure that the state grants and protects rights and freedoms evenly across social groups. The equal distribution of resources ensures that individuals' basic necessities are taken care of, thus enabling them to exert those rights and freedoms. Egalitarian societies have been demonstrated to perform better in fostering innovation and sustained economic growth, which is why inclusive institutions are considered key to nations' prosperity and wellbeing (Carter, 2014; Acemoglu and Robinson, 2012). In practice, however, politics and policymaking can empower some groups while marginalizing or excluding others. For example, those with greater organizational and financial resources may disproportionally influence policy making through lobbying (Baumgartner et al., 2009; Mahoney, 2007). The prevalence of private interest influence on state institutions entails the risk of state capture (Crabtree and Durand, 2017; World Bank, 2007; Hellman, 2000). As a result, powerful individuals, economic actors, or even organized crime can shape a nation's policies, legal environment, and economy to benefit their own private interests (Martini, 2014; Stigler, 1971).

Figure 4.3 shows the trajectory of inclusive institutions from 1900 to 2016 using V-Dems egalitarian component index. It ranges from 0 to 1, with zero corresponding to a complete absence of egalitarianism, while a score of one would indicate that equal protection of rights, equal access to power, and equal distribution of key resources have been fully achieved.

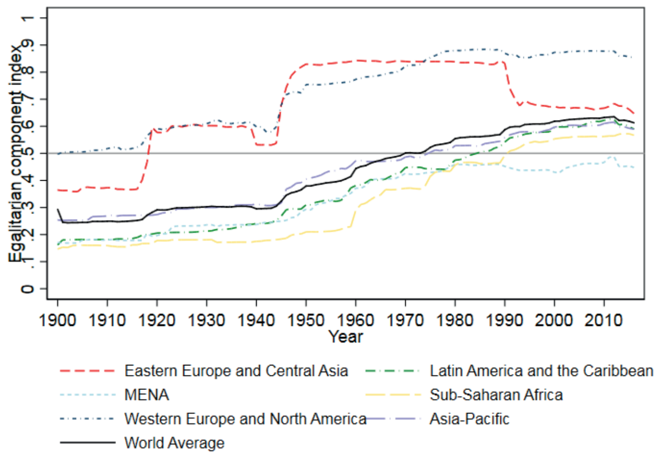


Figure 4.3. Inclusive institutions, global and regional trends, 1900-2016. Source: Coppedge et al. (2016).

To date, no country in the world ever has reached a perfect score on this index (V-Dem, 2017). Yet, on average, the world (black line) experienced a wave of expansion of egalitarianism after World War I, a tendency toward reversal during World War II, and a second, protracted but dramatic wave of expansion after the war. However, no automatism is observable between the expansion of political egalitarianism and economic equalities. For instance, in Western Europe and Northern America, the decline of the quality of inclusive institutions concurs with increasing income inequality since 2010.

Participatory decisionmaking implies that individuals from all social groups are equally capable of exercising their political rights and influencing the political and governing processes. Participatory institutions are considered important enabler for the implementation of 2030 Agenda, as it is important that all sectors and groups of society are be able to articulate the main challenges that they face. The risk of destabilization increases where political decision-making constantly excludes and marginalizes certain social groups. One illustrative example of this is the way in which the exclusion of unemployed youth from economic, social, and political opportunities contributed to protest mobilization in the Arab Spring movements (Abdalla, 2015; Asseburg and Wimmen, 2015; Breuer et al., 2014; Ayeb, 2011). Establishing participatory institutions is thus not only a goal in itself (SDG target 16.7) but also a task for successful implementation of other SDGs. There is still a need to ensure that all groups and sectors have the space and adequate mechanisms at their disposal to contribute to aligning, designing and implementing the SDGs.

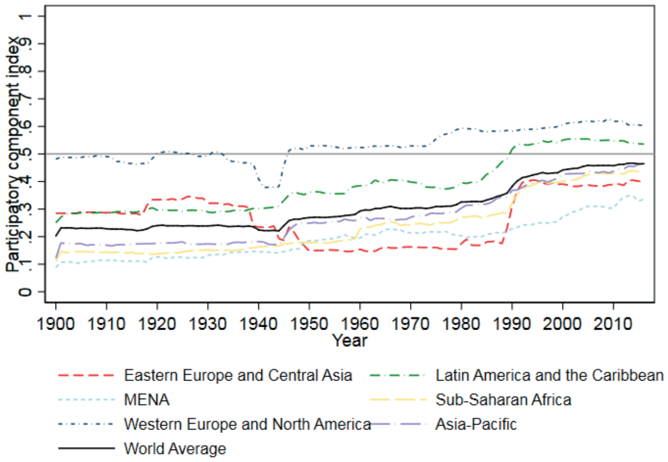


Figure 4.4. Participatory decision making, global and regional trends, 1900-2016. Source: Coppedge et al. (2016).

Figure 4.4 displays the levels of participatory decision making across the world from 1900 to 2016 using V-Dems participatory component index. The index captures three aspects of participatory decision making 1) the participation in civil society organizations, 2) the ability of citizens to decide on issues directly at the ballot box through mechanisms of direct democracy, and 3) popular participation and representation in sub-national level governments. Values run from 0 (total absence of participation) to 1 (full participation). As can be seen, on an average, the level of participation has steadily improved globally over the last century. The most dramatic changes in participation over time occurred in the region of Eastern Europe and Central Asia. The dissolution of the Soviet Union and the independence of its former constituent republics, triggered a rapid increase of participation in Eastern Europe and Central Asia, following which, levels of participation also broadened in other regions of the world, including Middle East and North Africa (MENA), Asia and the Pacific and sub-Saharan Africa. However, a high number of political regimes with limited participation persists and various countries, including some in Eastern Europe, face increasing illiberalism and democratic backsliding (Mechkova et al., 2018). Part of this trend is the shrinking space of civil society where regulations and laws over-regulate, limit and inhibit the funding and actions of civil society organizations (Poppe and Wolff, 2017)

4.2.2 Peace, conflict and state fragility

Historical analyses of various forms of violence show that violence has been declining over the past centuries (Pinker, 2011, chapter 5); Nevertheless, despite a general decline, these processes are prone to setbacks in individual regions and could possibly reverse even globally. While we observed a substantial decline of international violent conflicts between states after the end of the Cold War in 1990, intrastate conflicts have since then increased. However, given the current political tensions in global politics it does not seem too unlikely that this trend reverses. Figure 4.5 shows a global decline in battle-related deaths in the post-Cold War era. However, following the year 2005, which saw the lowest number of victims from battle-related deaths in recent history, the past five years, have seen a renewed rise in conflict-related fatalities which exceed even the highest levels from the post-Cold War era. This strong increase can be mainly attributed to the conflicts in Syria and the rise of ISIS in the wider Middle East (Allansson et al., 2017). Although in history more people have died from hunger and epidemics than from warfare, armed conflict and the instability which arises from war and post-conflict situations can be major facilitators of hunger and epidemics (Gates et al., 2012). The data of battle-related deaths described above account only for fatalities from direct violence, the death toll and suffering inflicted through the indirect consequences of armed conflict will be much higher.[3] Considering both the direct and indirect effects of major armed conflicts, battle-related death from wars and violent conflict remain a challenge in affected regions and geographical areas.

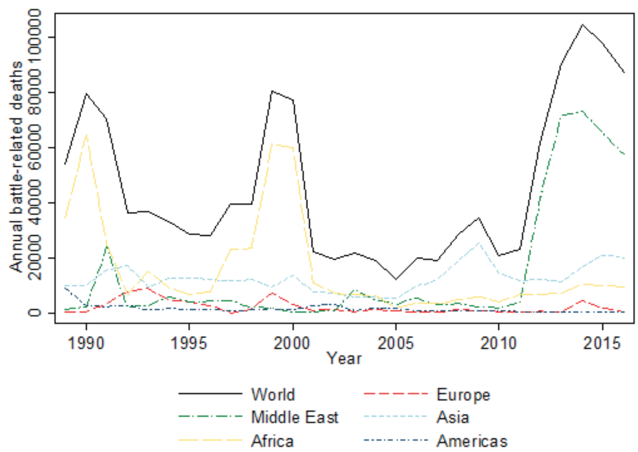


Figure 4.5. Battle-related deaths 1989-2016, own calculation based on Allansson et al. (2017).

[3] Rising levels of overeating (estimated 3 billion by 2030) is likely to be the next driver of death Harari, Y. N. 2017. *Homo deus: A brief history of tomorrow,* New York, Harper Collins E-Books.

Box 4.2. The negative externalities of wind power in Mexico: poor governance and social conflict.

Introducing new policies such as renewable energies can foster trade-offs between SDG and create social conflict if inclusive and integrated governance is missing. Following the liberalization of its energy market in 2013, Mexico has become a regional leader in the production of renewable energy (SDG 7). However, issues of social justice and peace (SDG 16) and land control by small-scale peasants (SDGs targets 1.4 and 2.3) associated with the production of wind energy were not integrated into Mexico's policy approach. The trade-offs and social conflicts related to the production of wind energy in Mexico were caused by inadequate multi-level and missing inclusive governance, which are characterized by top-down decision making within a weak institutional framework and exclusive decision-making.

Technical studies have identified the Isthmus of Tehuantepec in the federal state of Oaxaca as the most attractive region in the country to implement wind farms. At the same time, however, Oaxaca is one of the poorest Mexican states with 62% of its mostly indigenous population living under the poverty line and 23% living in extreme poverty. Wind energy planning has, this far, been a predominantly federal responsibility, with minor or no participation of the regional government (Oaxaca state) and local authorities and populations who are directly affected by the wind parks.

In view of Mexico's limited economic and technological capacities, it was considered essential to attract foreign private investment to develop the country's wind potential. After a long phase of state-led development starting from the 1990s, Mexico engaged in neoliberal structural adjustments. The liberalization of the energy sector and land tenure regimes paved the way for wind power as a profit-driven industry and enacted the introduction of private investment in the rural landscape of the Isthmus, which had previously mainly been organized through social and collective forms of property. As a consequence, multinational foreign enterprises emerged as the main protagonists in exploiting wind power.

Wind energy in Mexico is developing under a legal framework of self-supply (autoabastecimiento) that allows private power producers to partner with industrial off-takers, who invest in the project in order to benefit from a long-term fixed price on their electricity. By August 2015, the installed capacity in the Isthmus was 2160 megawatts (MW), from over 2000 wind turbines, out of which only seven were publicly owned.

Over the past years, the Isthmus region has experienced increasing socio-environmental conflicts that are not only threatening the continued expansion of wind development but also social stability. Following the initial negotiations between private foreign investors and the federal government, indigenous communities had made demands for comprehensive information about wind energy projects, to which the government did not respond. The resistance of local residents against large-scale wind energy projects is mainly targeted against the lack of formal participatory consultation (SDG target 16.7), illegal and unfair leasing contracts, and the meager compensations offered to land holders by private investors. While the worldwide average of payments to landowners fluctuates between 1 and 5% of wind farms' gross income, on the Isthmus these average between 0.025 and 1.5%. Furthermore, with the majority of energy generated going to industrial off-takers in distant cities, impoverished residents of the Isthmus are not directly benefitting from the product that is being produced on their lands.

Sources: Avila-Calero (2017), Huesca-Pérez et al., (2015), Hernandez-Cortez and Codero, (2014), Juárez-Hernández and León, (2014).

Achieving the ambitious objectives of the 2030 Agenda and beyond will only be possible if political instability and organized violence can be avoided or at least mitigated (Brundtland et al., 1987). Examining the Millennium Development Goals (MDGs), which preceded the 2030 Agenda, highlights that armed conflict and war are detrimental to many development outcomes in affected countries. Major intrastate conflicts usually stall economic growth and can destroy years of economic development as well as state structures which are needed to enable sustainable development. Similarly, violent conflicts tend to exacerbate undernourishment and increase child mortality (Gates et al., 2012). 90% of all civil wars are recurrences in previously conflict-ridden countries. Walter (2015) finds that every civil war that has started after 2003 (with the exception of Libya) has been a continuation of previous civil war. Thus, affected countries risk being caught in a negative spiral which undermines any efforts to achieve the 2030 Agenda (United Nations and World Bank, 2018). While positive cases of effective international strategies to support sustainable peace do exist, armed violent conflicts and war pose a threat of widening the gap between different countries or entire regions and puts the global ambition of the SDGs at risk.

Given that armed conflict can derail the transformation to sustainable development, it is important to target the circumstances which breed organized violence. During the past decades, academic research has provided a comprehensive assessment of the conditions which predict armed conflict (Hegre and Sambanis, 2006). Many of these conditions can be found among the targets and indicators described in the SDGs. This reveals an important circular relationship among many SDGs on one side as well as peace and stability on the other. Implementing the SDGs should coincide with substantive reduction in the risk of conflict outbreak. At the same time, however, conflicts that do occur will undermine the progress towards reaching many of the targets in the affected regions. It is thus essential to identify and work towards the targets which are linked with lower risks of violence and instability. Given the high risk of recurrence, parallel efforts need to be made to stabilize and end ongoing conflict as well as to support SDG implementation in post-conflict settings.

Among the most robust findings in the study of organized violence is the fact that conflicts appear most frequently in the poorest and most undeveloped regions of the world (Hegre and Sambanis, 2006). Establishing food security (SDG 1) and making economic growth inclusive (SDG 8) worldwide should therefore coincide with a substantial decrease in conflict risk. But economic growth alone will not be sufficient to decrease conflict incidence. For example, child mortality has been found to be a strong predictor of subsequent civil wars and political instability (Goldstone et al., 2010). Although child mortality is certainly not a direct cause of war, the statistical association can be understood as strong evidence that conflicts result from contexts of poor living conditions which leave large parts of the population excluded. Reducing child mortality substantially (SDG target 3.2) by using technical improvements will therefore not lead to a decline in conflicts. On a larger level, however, working towards universal health coverage (SDG target 3.8), can go along with a larger set of policies providing for inclusive social institutions that help promote peaceful societies.

It is important to promote inclusive political and social institutions and mitigate disparities in society (SDG 10 and SDG target 16.7). Aside from absolute deprivation, the equality and exclusion of specific social groups matters. There is increasing evidence that politically marginalized groups are more likely to engage in armed rebellion (Cederman et al., 2011). Similarly, economic inequality between ethnic, religious or other social identity groups appear to drive conflict (Buhaug et al., 2014). However, it is unlikely that economic inequality single-handedly causes violent conflict. It only causes the outbreak of violent conflict if combined with other factors such as social identities, access to resources and particularistic interests (Bartusevičius, 2014). Promoting political and economic equality within societies (SDG 10) and establishing or strengthening inclusive institutions (SDG target 16.7) should provide more stability to diverse societies and help reduce the risk of armed conflict.

Although democracy is not explicitly enshrined in the SDGs, democratic institutions are generally associated with considerable peace and stability. Democratic regimes are more stable in the long-run when compared to most autocratic regimes (Goldstone et al., 2010). Moreover, the empirical observation that democratic nations do not wage war against each other is one of the most established empirical regularities in international relations (Dafoe et al., 2013). Nevertheless, like most major transformations, changes in political regimes are often associated with internal conflict (Hegre et al., 2001). However, predominantly closed autocratic regimes that face an abrupt change of power are likely to cause internal war, whereas semi-open systems are less likely to face violence (Ziaja, 2017). This should serve as a cautioning observation against dramatic action for regime change.

However conflicts with high intensity violence are not the only threat to achieving and implementing the SDGs. Protests with a lower intensity of conflict such as local protests, riots and vandalism have been increasing during the last decade. This has been an overlooked phenomenon, which increasingly occurs across all types of states in the OECD and developing world in both democracies and autocracies. Highly mobilized social groups protest on an ad hoc-basis to complain about living conditions, for instance against the increase of food prices or unwelcome mega-infrastructure projects (see also Box 4.3). Local protests can be a blessing and a curse for sustainable development and peace, depending on the contextual circumstances. In contexts with functioning and open political institutions they can be important means to channel citizens' interests and challenge vested interests, which would have otherwise undermined common goods. At the same time, powerful local interests can also challenge common goods, for instance protests against renewable energy generation, opposition against improved electricity grids in Central and Southern Germany. Where local conflicts meet challenging societal structures they are likely to add-up to major incidences of violence. For instance, the intensity of violence is likely to increase where political institutions fail to include peoples' interest and unfavorable structural conditions, such as increasing inequalities and an exponential population growth (which increases the number of young and mobilized people) evolve.

All in all, the observation that implementing many SDGs should go along with a reduced risk of armed conflict is comforting. Nevertheless, SDG implementation can only serve as a long-term strategy of conflict prevention and not for managing and stopping violent conflict. Even with major advancements toward sustainable development, conflicts will always occur, especially in turbulent times of change. Recent projections contend that with the most optimistic scenarios, the number of conflicts worldwide can be substantively reduced, but war and instability cannot be prevented completely (Hegre et al., 2016). In each affected location or region, these conflicts may put sustainable development in jeopardy. In these situations, conflict will have to be contained and resolved as quickly as possible. This will require substantive efforts by the international community and reliance on well-established tools of conflict management: robust peacekeeping engagements paired with concerted diplomatic efforts to end the conflict.

The international community is not empty handed when it comes to conflict management and resolution. Simulations of global peacekeeping allocation suggest that extensive international commitment and financial contributions to peacekeeping can substantively reduce the level of conflict worldwide over the next decades (Hegre et al., 2011). There is increasing evidence that robust and well-staffed peacekeeping missions are able to deescalate ongoing conflicts and protect the civilian population (Hultman et al., 2014; Hultman et al., 2013). These findings suggest that states should build the capacity and be willing to contribute to these missions. Alongside peacekeeping operations, the international community will need to patiently push for diplomatic solutions to ongoing conflicts and support mediated conflict resolution. Third party mediation appears to be associated with a higher chance of peaceful settlement and more durable peace (Ruhe, 2018). Upon successful resolution, peacekeeping operations are again an important policy response to ensure that conflicts do not

Box 4.3. Reforms needed for governing the Transformations Towards Sustainability.

Basic reforms for the economy and governance need to guide the deep changes needed to implement the 2030 Agenda. They will be the basis for transformative governance and guide economic instruments and policies as well as. TWI2050 will develop principles of transformative governance further in its future work.

ECONOMIC REFORMS

Problems to solve	Reforms needed
Significant public investments needed	Increasing and stabilizing domestic tax revenues
Doubling local, national, 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

However, the Transformations Towards Sustainability require not only capable institutions, inclusive 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:

GOVERNANCE REFORMS

Problems to solve	Reforms needed
Sustainability transformation as a civilizational challenge	Four normative innovations: • Earth system responsibility • Global commons perspective – transnational fairness & justice • Anticipate impacts of decisions for many generations to come • Culture of global cooperation and norm 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 policymaking across borders, sectors and SDGs	Polycentric, multi-scalar governance and integrated management
Deep transformations lack public legitimacy	Investment in drivers of motivational change: • Normative triggers: How can we accept that? • Demonstrating success • Attractive future narratives
Dysfunctional and weak international organizations (IOs)	Reinforcement of multilateral cooperation; strengthen autonomy of IOs

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 and eroding social contracts
5. Disruptive dynamics	Deep change producing legitimacy challenges

recur (Fortna and Howard, 2008; Fortna, 2004). Furthermore, improvements towards good governance principles and improvements of rule of law (e.g., SDG target 16.3) can act as important stability anchors in fragile societies (Hegre and Nygård, 2015; Walter, 2015).

4.3 Achieving SDGs 6, 7, 11, 12 and 15 - governing interlinkages as an element of sustainability transformations

This section argues that one element of the sustainability transformation relates to governing interlinkages among multiple SDGs. It suggests that governing interlinkages among the 2018 HLPF priority SDGs 6, 7, 11, 12, and 15 can be informed by the evolving debate on governing the water-energy-food (WEF) nexus. Section 4.3.1 lays out the need for governing interlinkages related to the 2018 HLPF priority SDGs 6, 7, 11, 12, and 15 and introduces into the WEF nexus debate. Section 4.3.2 provides selected examples of WEF nexus situations and related governance challenges and approaches. Section 4.3.3 discusses elements of and obstacles towards governing interlinkages in general and the WEF nexus in particular. Section 4.3.4 concludes and reflects to what extend the insights gained can be generalized for dealing with interrelated goal systems beyond the WEF nexus.

4.3.1 Why governing interlinkages?

In Chapter 3, interlinkages related to the 2018 HLPF priority SDGs, namely SDGs 6, 7, 11, 12, and 15 were discussed. This section further explores what such a systematic perspective implies for governance. By doing so it largely draws on an evolving debate on governing the water-energy-food (WEF) nexus (e.g. Pahl-Wostl, 2017; Weitz et al., 2017). The WEF nexus debate discusses how the simultaneous provisioning of water (SDG 6), energy (SDG 7), food security (SDG 2) and of a world with less than 2 degree Celsius global warming (SDG 13) increases pressures on various input dimensions, such as water resources (SDG 6) as well as land use, soils and biodiversity (SDG 15) (Müller et al., 2015a) (Figure 4 .6). Hence, SDGs 2, 6, 7, 13 and 15 can be considered to be at the center of the WEF-climate nexus debate (in the following referred to as WEF nexus). However, the sustainable provisioning of water, energy, food and other ecosystem services is a precondition for sustainable cities (SDG 11) and WEF nexus challenges become also highly visible in cities. Furthermore, sustainable consumption and production (SDG 12), especially of food and non-food crops, is also closely interlinked with resource use and ecosystem provision (SDGs 6 and 15). In the following we draw on the WEF nexus debate, even if SDG 2 (no hunger) was already included in the 2017 HLPF review and SDG 13 (climate actions) will be included in 2019 HLPF review. We assume that a WEF nexus situation is present when at least two of the four output dimensions, water, energy, food security and climate change mitigation are being pursued simultaneously and if this produces synergies or competing demands for natural resources.

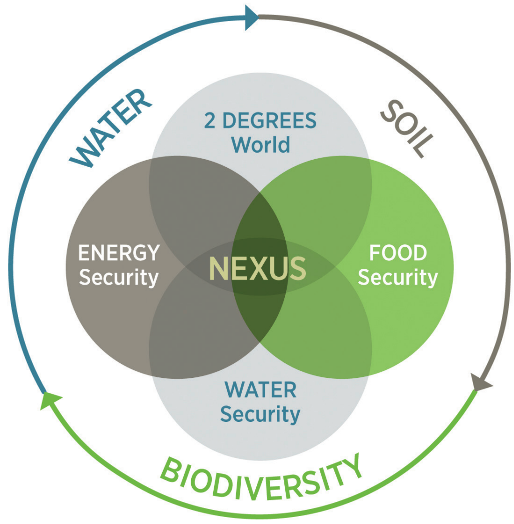


Figure 4.6. The water-energy-food-climate nexus. Source: Reprinted from Müller et al. (2015b), with permission from Elsevier.

As mentioned in Chapter 3 pursuing different goals simultaneously may entail synergies and trade-offs. For example, subsidies for electricity in arid regions (SDG 7) can contribute towards increasing local food security, SDG 2) through irrigation. However, this strategy may at the same time go along with falling groundwater tables and thus counteract the sustainable and efficient use of water resources (SDG 6) (Müller et al., 2015a; Shah et al., 2003). In water-scarce regions, water pricing e.g., through cap-and-trade schemes, can be an efficient instrument to balance water use between agriculture, private households, industry and ecosystems (Burdack et al., 2014). However, in poor countries increasing costs for water may have negative effects on poverty (SDG1) and food security (SDG 2). Another example are the side effects of a potential large-scale deployment of bio-energy (BE) with carbon capture and storage (CCS) in order to generate renewable energy and achieve negative carbon dioxide emissions. In fact, most of the scenarios that envision limiting global warming to a maximum of 1.5° Celsius (SDG 13) assume the large-scale use of BECCS (Smith et al., 2015; Fuss et al., 2014). It is expected that this will considerably increase pressures on land use, ecosystems and biodiversity (SDG 15), water resources (SDG 6), and food prices (SDG2) (Humpenöder et al., 2018; Field and Mach, 2017; Popp et al., 2017; Bonsch et al., 2016).

However, certain actions related to SDGs 6, 7, 11, 12 and 15 may also generate synergies and co-benefits for other SDGs. For example, investments in wastewater treatment with energy co-production may simultaneously contribute to increasing water (SDG 6) and energy (SDG 7) security, public health (SDG 3) and contribute towards more sustainable cities (SDG 11) (Never and Stepping, forthcoming; Never, 2016b; Never, 2016a). Dietary change can reduce pressures on land and water resources (SDGs 6, 15), reduce nitrogen pollution (SDG 12) and generate health co-benefits (SDG 3) (Humpenöder et al., 2018). Such co-benefits can be drivers of change since actions related to one SDG may contribute directly or indirectly towards further SDGs.

Maximizing synergies and mediating trade-offs is significantly related to investments in infrastructure and technology, but it is also a governance task. Nexus thinking therefore argues for the need to 'overcome' decision-making in silos and to enhance policy coherence across sectors, levels and actors (Rasul and Sharma, 2016; Hoff, 2011). Authors hence stress the need for cross-sector coordination, multi-level as well as multi-actor governance, taking into account the geographical scale of the respective nexus problem (Pahl-Wostl, 2017; Weitz et al., 2017; Müller et al., 2015a). Drawing upon Paavola (2007) and Müller et al. (2015a), we understand WEF nexus governance as a dynamic and recursive process involving state and non-state actors who establish, reaffirm or change institutions to resolve conflicts and negotiate political decisions in a way that takes into account interdependencies between soil, water and biodiversity systems in the provision of water, energy, food and climate security.

However, as Weitz et al. (2017) point out, our understanding of what governing the WEF nexus means and under which conditions it works or not remains limited. Furthermore, many barriers exist towards governing the WEF nexus, including vested interests, power asymmetries and transaction costs. This section therefore summarizes initial insights of research on governing the WEF nexus.

4.3.2 Examples of WEF nexus situations and related governance challenges and approaches

The following examples provide snapshots of three WEF nexus situations and related governance challenges and approaches. The three examples cover both developed and developing countries, rural and urban areas, situations characterized by negative cross-sector externalities as well as an example wherein technology innovation may generate cross-sector co-benefits. Thus, they cover a broad spectrum of different nexus situations and related governance challenges and approaches.

Example 1: Voluntary agreements to reduce nitrate from agriculture into drinking water sources in Germany

In many developed countries, the intensification of agriculture and the increased use of nitrogen and phosphorous for food production (SDG 2) has led to a heavy influx of pollutants into surface and ground water (Bodirsky et al., 2014). This can have detrimental effect on water quality (SDG 6) and biodiversity (SDG 15) in water bodies and potential negative health effects (SDG 3) if nitrate concentrations in the drinking water exceed the critical limits. In Germany, since 2008 on an average, 18% of all measuring points in groundwater bodies exceed the threshold value of 50 milligrams nitrate per liter of as set by the European Nitrate Directive (UBA, 2017). As a consequence, drinking water suppliers are expecting a considerable rise in water treatment costs, and hence in drinking water prices in future.

In order to avoid additional treatment costs and nevertheless comply with the German Drinking Water Ordinance, in recent decades many water suppliers have concluded voluntary agreements with farmers in their areas of operation in order to induce good farming practices that minimize nitrate leaching into water bodies. These Measures include needs-based fertilizer planning, sealed storage for manure and special technologies for liquid manure application. They are financed by the water suppliers. In North Rhine-Westphalia, water suppliers can offset their expenses against the water abstraction levy they pay to the federal state. In many regions, the combination of the underlying European and German regulations and these voluntary agreements with the private sector have shown positive effects. Important prerequisites are that use rights are clearly stipulated, that stakeholder participation is taken seriously and that a good data basis as well as reliable monitoring of compliance are in place (Richerzhagen and Scheumann, 2016). An example is the Wahnbachtalsperre, a drinking water reservoir, which supplies to the city of Bonn and successfully meets the required standards (ibid.).

In contrast, in other regions such as Lower Saxony - an area of intensive livestock farming - similar programs led to some initial declines of nitrate concentrations in groundwater in the early 2000s. However, since 2007 nitrate levels have been rising again (Pahl-Wostl, 2017). Reasons for this include a continuing intensification of livestock production, aggravated by the increasing cultivation of energy plants, like maize in particular.

This also reveals more fundamental problems with existing subsidy schemes, especially as part of the EU Common Agricultural Policy (CAP). Despite some decoupling of subsidies from production, there are still incentives for agricultural intensification, while e.g., nitrogen pollution control is insufficiently enforced. Negative health effects from nitrogen compounds include health damages from respiratory diseases as well as the loss of aquatic ecosystem productivity and fish production. Nitrogen-related pollution accounts for economic damages of 0.3–3% of gross world product (Bodirsky et al., 2014; Sutton et al., 2013; Sutton et al., 2011). In addition, the pressure for intensification and nitrogen fertilizer use is further increased by subsidies for maize production as part of German and European legislation on biomass-based renewable energy production. Given the breach of the Nitrate Directive, in 2016 the European Commission has initiated treaty violation proceedings against Germany (Awater-Esper, 2016). German taxpayers might thus have to cover a fine of several billion Euros.

Example 2: Payment for ecosystem services to manage the WEF nexus related to hydropower plants - The Hidrosogamoso case in Columbia

Payment for Ecosystem Services (PES) is one popular instrument to internalize externalities, also across different resource uses. This raises the question of whether the instrument is capable of fostering an integrated WEF nexus perspective. This question was studied using the case of the Hidrosogamoso hydropower plant (HPP) in Colombia (Rodriguez-de-Francisco et al., under review; Rodriguez-de-Francisco, 2016). The Hidrosogamoso HPP uses PES to pay for the conservation of upstream forests in order to improve water provision, reduce sedimentation and offset environmental impacts. An analysis of the socio-environmental impacts (costs and benefits) for different actors at different scales up- and downstream of the HPP shows that the PES scheme successfully provides water security (SDG 6) for hydropower production (SDG 7). However, despite the PES scheme and an Environmental Impact Assessment (EIA), the HPP negatively affects the water and food securities of marginalized communities further downstream. In particular, the principle of prior and informed consent was not applied in the EIA. The consequent impact of the HPP led to demonstrations and protests, which, however, were suppressed by the government. It turns out that the Hidrosogamoso public-private partnership has been able to successfully sell the HPP as positive contribution to national energy security (SDG 7) and a contribution to combating climate change (SDG 13), while also highlighting the benefits of the PES scheme for local biodiversity protection (SDG 15). However, at the same time the basin scale including downstream water (SDG 6) and river-related food (SDG 2) security is neglected in the company's discourse. The case therefore illustrates how actors' strongly divergent economic and political powers lead to prioritizing certain securities related to the WEF nexus, while suppressing others. Thus, examining the on-the-ground politics of PES and the WEF nexus is key to understanding their impact on the equitable and sustainable provision of water, energy and food in the everyday lives of millions of resource users. It becomes clear that a market mode alone did not solve the nexus challenges in this case, and that additional hierarchical modes of governance are needed to either balance the competing demands or at least provide for compensation mechanisms for those who lose out in this nexus situation.

Example 3: The urban nexus: Promoting wastewater treatment and energy co-production in Indian growing cities

Wastewater treatment plants in cities and settlements contribute towards public health (SDG 3), protecting water resources and ecosystems from pollution (SDGs 6, 15) and securing future water supplies (SDG 6). However, many standard technologies, such as activated sludge, consume considerable amounts of energy. At the same time, significant potential for energy saving, and even energy co-generation, exist in wastewater treatments plants, e.g., by means of biogas or combined heat and power production in the treatment plant. A large sewage treatment plant can cover up to 80% of its own energy requirements and thus contribute towards SDGs 7 and 13. For combined heat and power production, even energy self-sufficiency is possible (Never, 2016b). However, in upper middle income countries only 38%, and in least developed countries only 8% of the wastewater is treated in the first place (Sato et al., 2013), and energy-saving technologies remain very rare in wastewater treatment in developing countries. For instance, in India only 30% of the population is connected to sewerage systems and only 10% of the wastewater produced is treated. At the same time, planned and unplanned urbanization proceeds at a high rate, implying a steadily growing number of people that needs to be connected to sewerage systems.

Research on wastewater treatment in Indian cities reveals a number of obstacles towards wastewater treatment in general, and for energy co-production in such plants in particular (Never and Stepping, forthcoming; Never, 2016b; Never, 2016a). First, there is lack of incentives to invest in wastewater treatment in the first place, for instance given that no cost-covering wastewater tariffs are in place. Second, regulations are not conducive towards energy co-production as in India no standards exists for sludge disposal and the reuse of treated wastewater. There is also no feed-in tariff for biogas and tender procedures hinder innovation. Third, capacities at local level are usually low, there is a high turn-over of positions, and risk aversion and old management paradigms prevail. Hence, water pricing and subsidy reforms, binding discharge standards and regulations on energy savings would be key instruments to promote wastewater treatment as well as the diffusion of energy-efficient technologies in wastewater treatment. Research elsewhere shows that standards and regulations are especially effective when they are introduced sequentially and monitored locally. This should go hand-in-hand with using cost arguments and fostering a lifecycle-oriented mindset. Climate funds could be a means to finance resource-efficient solutions. Still, while the hope would be that a 'Mercedes Benz' solution of wastewater treatment with energy co-generation would pay-off in the long-run, the Indian case nevertheless does raise the question of whether the priority should not be to cover as many people with conventional wastewater treatment in the first place.

4.3.3 Elements and challenges of WEF nexus governance

There is a broad consensus in the WEF nexus literature regarding the need for cross-sector coordination and multi-level governance, taking into account the geographical scale of the respective nexus problem (Pahl-Wostl, 2017; Tosun and Leininger, 2017; Weitz et al., 2017; Leck et al., 2015). However, there is no consensus on what cross-sector and multi-level WEF nexus governance entails and under which conditions it comes about (Weitz et al., 2017). On the contrary, various schools of thought have different understandings of the underlying concepts of coordination and governance and highlight different aspects related to them. For instance, Weitz et al. (2017) identify seven relevant schools of thought on integrative environmental governance, including literature on environmental policy integration, inter-organizational relations, institutional interaction and interplay, policy mixes and smart regulation, groups of regimes, meta-governance and orchestration or landscape governance. Concepts originating from this literature may contribute towards understanding challenges related to governing the WEF nexus, even if they have rarely been applied to WEF nexus problems.

However, despite all differences, various governance literature distinguishes three stylized types of governance modes upon which coordination may rely: hierarchies, markets and networks. In the following, we argue that coordination across sectors and levels may be supported by combining different governance modes and related policy instruments. Therefore, the three governance modes are briefly introduced at this stage. Hierarchies, markets and networks can be distinguished according to the types of actors involved (state, non-state) and the formality or informality of institutions (rules) upon which they rely (Figure 4 .7). Non-state actors can be further broken down into the private sector on the one hand and civil society on the other. In hierarchies (such as state organizations or private companies) coordination is achieved through top-down orders based on legitimate authority (Pahl-Wostl, 2015). Market governance relies on prices to coordinate exchange between self-interested actors (Williamson, 1985). In networks, coordination is achieved through interactions "between actors whose interorganizational relations are ruled by the acknowledgement of mutual interdependencies, trust and the responsibilities of each actor" (Bouckaert et al., 2010: 36).

In the following, we identify a number of challenges and associated elements of governing SDG interlinkages in general, and the WEF nexus in particular, drawing on various literature.

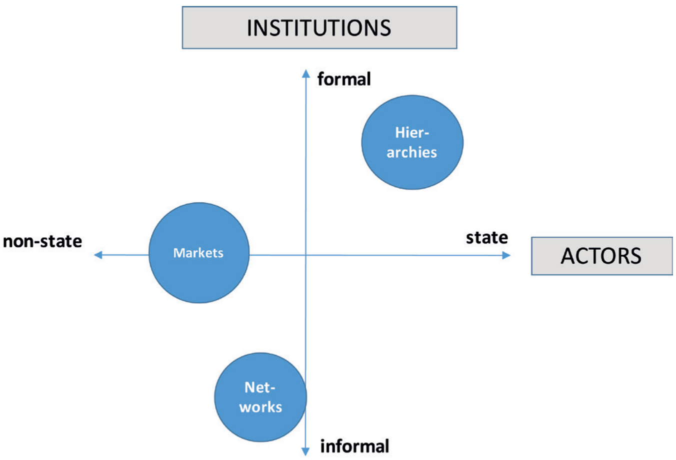


Figure 4.7. Governance modes. Source: After Pahl-Wostl (2009).

Element 1: Design policy mixes that take SDG and WEF interlinkages into account

The first challenge to governing SDG interlinkages in general and the WEF nexus in particular is that multiple policy objectives can usually not be achieved by a single policy instrument. Policy instruments can be grouped into regulatory (e.g., standards), market-based (e.g., pricing) and informational (e.g., awareness raising) instruments. According to economist Jan Tinbergen, there should be as many independent instruments as there are targets or goals. Hence, any simultaneous pursuit of several policy objectives should rely on an adequate policy mix that takes cross-sector interdependencies and related externalities into account.

According to the policy-mix literature, in an ideal world, an adequate policy mix relies on the consistency of its different elements (Rogge and Reichardt, 2016). This includes 1) the alignment of policy objectives, 2) a consistent instrument mix: regulative, market-based and informational instruments to reinforce rather than undermine each other and 3) consistency of the instrument mix with policy strategy. In addition to a consistent policy mix, coherence of processes involves synergistic and systematic policymaking and implementation processes along the entire policy cycle contributing towards policy objectives (Tosun and Leininger, 2017; Rogge and Reichardt, 2016). Policies on paper do not suffice, if they are not well-implemented.

Case studies on governing the WEF nexus give multiple indications that adequate policy mixes matter. In the case of the Wahnbachtalsperre (Example 1 above), the combination of regulatory instruments and voluntary agreements helps reducing nitrate leaching from agriculture into the drinking water reservoir. In the Hidrosogamoso case (Example 2), a PES scheme contributes towards mitigating negative externalities of land use upstream on the hydropower plant. However, additional instruments such as an Environmental and Social Impact Assessment (ESIA) and ideally the application of the principle of prior and informed consent would be needed to address the effects of the hydropower plant on water and food security downstream (Rodriguez-de-Francisco et al., under review). In order to foster wastewater treatment with energy co-production in India (Example 3), reforms of standards and water pricing instruments could potentially foster transitions to innovative wastewater systems. It is also important to note that instruments which may be first-best solutions from a single-sector perspective, e.g., a GHG tax for climate change mitigation, may not be adequate in a multi-sector, multi-objective context. In line with Tinbergen, such a tax should be combined with other effective instruments to assure the achievement of multiple goals. For example, ambitious climate change mitigation (SDG 15) needs to be combined with biodiversity conservation measures (SDG 15), protection of water resources (SDG 6), e.g., through water pricing, and compensation payments for poor food consumers (SDG 2), to avoid negative side-effects (Humpenöder et al., 2018).

An important aspect of an adequate policy mix is the consideration of subsidy reform and a general reduction of harmful subsidies in pursuing multiple SDGs. As mentioned above, agricultural policies in many OECD countries provide incentives for intensive production, excess nitrogen and phosphorus use and related water and air pollution as well as biodiversity loss. Existing fossil-fuel subsidies in many countries worldwide effectively create a negative price on emissions and deter the spread of renewables (Jakob et al., 2015). Fuel subsidies for water pumps are meant to support farm income in Northern India, but lead to falling groundwater tables (SDG6) (Shah et al., 2003). The reduction of these harmful subsidies, and financial reforms in general, would reduce the pressure on public budgets and create opportunities for introducing more effective SDG policy instruments as well as compensation payments for low-income groups (e.g. Klenert et al., 2016).

Element 2: Foster horizontal and vertical coordination within the public sector

A second challenge of governing SDG interlinkages in general and the WEF nexus in particular is decision-making in silos within the public sector. Hence, there are calls for greater horizontal and vertical coordination among public sector agencies when food, water and/ or energy security are at risk. In this context, coordination can be understood as the "extent to which organizations attempt to ensure that their activities take into account those of other organisations" (in Bouckaert et al., 2010: 15; Hall et al., 1976: 459). Horizontal (or cross-sector) coordination refers to coordination among organizations at the same hierarchical tier of government (e.g., between ministries or agencies). Vertical coordination (or multi-level governance) refers to coordination across levels of government (e.g., across municipal, provincial, national and international levels).

In general, the public sector constitutes a hierarchy and therefore also strongly relies on hierarchy-type coordination mechanisms (such as orders, etc.). This pertains in particular to vertical coordination when higher level bodies give hierarchical directions to lower level bodies. However, this notwithstanding, market- and network-type coordination mechanisms also play important and maybe increasing roles in public sector coordination (Bouckaert et al., 2010). This pertains in particular to horizontal coordination.

Horizontal coordination is primarily of a voluntary nature and therefore it relies strongly on market- or network-type governance mechanism (Bouckaert et al., 2010). Market-type mechanisms are based on price, competition and supply and demand (Bouckaert et al., 2010: 43). Network-type coordination depends on bargaining, negotiation and mutual co-optation. It may be supported by different mechanisms "ranging from simple information exchange between bodies, to platforms for concertation to negotiation, and to joint decision-making bodies and even joint organizations" (Bouckaert et al., 2010: 46). Horizontal coordination across sectors may furthermore be easier to achieve if it takes place in the shadow of hierarchy, for instance if a decision has to be ratified by a minister or the cabinet (Scharpf, 1993).

The nitrate (Example 1) and the wastewater (Example 3) nexus situations above illustrate governance across different jurisdictional levels. They show how national and even supranational standards may provide important framework conditions for addressing local nexus situations.

Element 3: Match the scale of the WEF nexus problem

Many WEF nexus situations pose an additional problem to vertical and horizontal coordination in and by public sector organizations given that physical interdependencies of WEF nexus problems often do not usually coincide spatially (or temporally) with jurisdictional boundaries. Depending on the WEF nexus problem at hand, the spatial scale of these externalities can even be of transboundary or globally teleconnected nature (Müller et al., 2015a). In such cases, WEF nexus governance might require action beyond single countries and span across regions through international trade of goods and services (e.g., virtual trade in water, Allan, 2003). Hence, governing the WEF nexus may require horizontal coordination across affected jurisdictions or countries sharing a transboundary resource or even across teleconnected nexus situations.

More generally spoken, WEF nexus problems might require multi-scalar governance or for that matter cross-scale interactions, e.g., across spatial (or temporal) and jurisdictional scales. Scale can be understood as the spatial, temporal or other analytical dimensions used to measure or analyze a phenomenon. Levels are "…units of analysis that are located at different positions on a scale" (Cash et al., 2006: 8). In political science, multi-level governance is usually thought of as governance across levels on the jurisdictional scale (e.g., across municipal, provincial, national or inter-government levels). However, whenever jurisdictions have to coordinate in order to match other spatial or temporal scales, this can be understood as multi-scalar governance. In fact, next to the so-called type I onion model of multi-level governance of nested general-purpose jurisdictions, so-called type II multi-level governance arrangements may also exist. These type II arrangements are task specific, while their spatial scale may transcend general-purpose jurisdictions (Marks and Hooghe, 2004). An example is that of river basin organizations, which typically add an additional layer of governance across general-purpose jurisdictions (Huitema and Meijerink, 2017) and it has been argued that interstate (Burdack et al., 2014) or international river basin commissions (Dombrowsky et al., 2016; UNECE, 2015) could play a particular role in governing the WEF nexus in interstate or international river basins.

A related concept in this context is the idea of landscape governance, which refers to the interconnections between socially constructed spaces (the politics of scale) and 'natural' conditions of places (Görg, 2007). The latter might be of interest for WEF nexus analyses by highlighting the politics behind interconnected social and ecological systems.

Case studies on WEF nexus situations illustrate the crucial importance of governance not only across levels, but also across scales, taking the respective scale of the WEF nexus problem into account. As the Hidrosogamoso case (Example 2) illustrates, energy planning may take place at different spatial scales than planning for integrated water resources management, which may lead to cross-scale conflicts (see also Hensengerth, 2015 for a transboundary case). As such, given the scale dimension, the WEF-climate nexus and other biophysical SDGs add a particular requirement for governing interlinkages across scales.

Element 4: Governance beyond the government: WEF nexus governance as multi-actor and polycentric governance?

Finally, WEF nexus governance is usually not only about the government, but the private sector and civil society may play important roles. As mentioned above, hierarchies, markets and networks can be distinguished according to the types of actors involved (state, private sector, civil society) and the formality or informality of institutions (rules) upon which they rely. Each mode comes along with strengths and weaknesses. Therefore, it has been suggested that synergistic combinations of different governance modes may meet coordination challenges in complex resource or WEF nexus situations better than in one single governance mode (Weitz et al., 2017; Pahl-Wostl, 2015). Forms of governance that try to combine the strengths of each governance mode in a complementary way may also be stipulated as hybrid governance (Pahl-Wostl, 2015). The successful self-governance of local common pool resources by local communities studied by Ostrom (1990) is an example of the sustainable governance of natural resources beyond states and markets. Leach et al. (2007) also argue for governance models with more dynamic and reflexive processes that incorporate norm setting of various types of actors and herewith move beyond the linear and state-centric governance model of decision-making. Furthermore it is sometimes suggested in the literature that the so-called 'boundary institutions' or 'intermediaries' that bring different stakeholders together may play a special role in governing cross-sector linkages (Hoff, 2011). Also at the international level, an increasing role of non-state actors in environmental governance can be observed. This phenomenon has been referred to as transnational governance (e.g., Chan et al., 2016).

Against the backdrop of the need for multi-sector, multi-level, multi-scalar and multi-actor governance, it has been suggested that WEF nexus governance would benefit from polycentric and adaptive governance (Gallagher et al., 2016). Following Ostrom et al. (1961), polycentric governance systems are characterized by multiple centers of authority and distribution of power, which at the same enter into competitive relationships, contractual arrangements or cooperative undertakings. Thus, such polycentric arrangements may be conducive towards governing the WEF nexus, which requires relating different types of actors, sectors and levels of decisionmaking. Adaptive governance refers to the ability of a governance system to alter processes and to adapt structural elements as a response to current or anticipated changes in the social or natural environment (Pahl-Wostl, 2015; Dietz et al., 2003), a feature that may also be conducive towards governing the WEF nexus. Polycentric governance may also contribute to adaptive governance (Pahl-Wostl et al., 2009). At the same time, it should also be mentioned that polycentric governance might not be good per se (Thiel, 2017), and the relevance of the concept for WEF nexus governance should be further studied in future.

Element 5: Presence of generic good governance principles

There are indications that governing trade-offs between different policy objectives is easier, if meta-governance or good governance principles, such as transparent, accountable, and inclusive institutions are in place (Weitz et al., 2017). Hence, WEF nexus governance may be supported by the presence of meta-governance principles as reflected in SDG 16 (target16.6: 'Develop effective, accountable and transparent institutions at all levels' and target 16.7 'Ensure responsive, inclusive, participatory and representative decision-making at all levels' as well as by multi-stakeholder partnerships call for in SDG 17 (Section 4.2)). It can furthermore be argued that governing of interlinkages relies heavily on the existence of rule of law and enforcement of rules and institutions. The Hidrosogamoso case (Example 2) illustrates how failing to apply the principle of prior and informed consent may lead to conflict with affected communities.

4.3.4 Obstacles towards governing SDG interlinkages and the WEF nexus

Obviously, multiple obstacles towards governing interlinkages exist. Based on their comprehensive evaluation of the literature on Integrative Environmental Governance, Weitz et al. (2017) highlight the following challenges for governing the WEF nexus: 1) negotiation usually take place among actors with unequal power, 2) nexus governance may be inhibited by the transaction costs of involving all affected actors, and 3) that solutions may simply lie outside the concerned WEF nexus sectors. These and additional barriers have been illustrated by various case studies on different types of nexus situations (Examples 1-3). Research on developing countries also confirms these obstacles, but highlights additional challenges in these settings in dealing with WEF nexus problems that pertain to low state and implementation capacities (Section 4.2) as well as lack of data related to natural resource use (summarized in Dombrowsky et al., 2016). The latter makes the assessment of externalities and the design of responses obviously much more difficult.

Overall, in dealing with trade-offs it has to be acknowledged that competing demands and conflicting interests over natural resources may not always be overcome and may require compromises to mediate such trade-offs instead of solving them. The larger the extent (spatial, sectorial or temporal) of a trade-off is, the more winners and losers will be produced through a decision and the more difficult it will be to mediate the trade-off; or the higher the time urgency is to achieve a goal (for example climate action), the costlier it will be to delay action. Hence decision-making of how to deal with existing trade-offs requires a critical reflection process of the competing demands and interests to arrive at justifiable recommendations regarding the prioritization and sequencing of policy actions. Norms and ethical criteria may differ between contexts, depending for example on the social contract on which a society is based, or on the cultural norms that are prevalent in this society. Mediating trade-offs requires dealing with these three dimensions: 1) "How to deal with the trade-off?" (procedural dimension), 2) "Who is eligible to take decisions?" (legitimization dimension) and 3) "For whom are decisions taken and what compensation mechanisms may be applicable?" (justification dimension) (Breuer et al., 2017).

4.3.5 Conclusions

Dealing with the synergies and trade-offs related to the pursuit of interrelated goal systems – and hence governing interlinkages among various SDGs – is one important element of a transformation towards sustainability. The WEF nexus debate arguably provides important insights for simultaneously pursuing HLPF SDGs 6, 7, 11, 12 and 15. Governing interlinkages may require adequate policy mixes, including comprehensive reforms of public finance and existing subsidy schemes, and fostering multi-sector, multi-level, multi-scalar and multi-actor governance processes. It is likely that this would be supported by synergistically combining the strengths of hierarchical, market and network governance within polycentric governance arrangements. It furthermore relies on effective governance capacities and arguably the presence of transparent and inclusive institutions. However, governing interlinkages also needs actively addressing the role of asymmetrical power balances and the politics behind interconnected social and biophysical systems. While these arguments may hold in general for implementing the system of 17 interrelated goals of the 2030 Agenda, governing the SDGs related to the WEF nexus requires particular attention to the scale of physical interdependencies and relies on adequate data and information to inform decision-making.

In view of the HLPF's sectoral approach towards the thematic reviews, the section also highlights why we should not limit ourselves to monitoring individual SDGs.

4.4 Three bifurcations on the road to sustainability

This report shows that a major transformation towards sustainability is both necessary and possible. The past few decades have seen many of the foundations laid for transitioning to sustainability: Technologies, transformative networks of actors, mental models, sectoral roadmaps for sustainable transformation (e.g., in energy management, the mobility sector, the agricultural industry) and entrepreneurial business models geared towards sustainability have been developed in many countries. The 2030 Agenda and the Paris Agreement can be considered the pillars of a global social contract for the transformation towards sustainability in the 21st century. "The conditions of possibility" (Immanuel Kant) for this transformation are now in place. From this perspective, the global sustainability evolution has succeeded and many of our societies are now at a tipping point where they can step up the pace of transition towards implementing the 2030 Agenda and the Paris Agreement. This tipping point situation is characterized by three major bifurcations: The transformation towards sustainability, nationalist counter-transformations and the far-reaching dynamics of the digital transformation.

4.4.1 Major challenges in the transformation towards sustainability

In many countries the forerunners and pioneers of the transformation to sustainability are not yet large and powerful enough to direct the economy and society as a whole onto sustainable pathways. As in other epochal transitional phases, such as the "transformation of the world in the 19th century" (Osterhammel, 2009) from agrarian to industrial societies, there can be great leaps forward as well as setbacks – even in parallel. Deep transformations are times of historical discontinuity based on a concurrence of multiple changes (*Häufigkeitsverdichtungen*) in many areas of society and the economy towards the formation of a new societal regime (Messner, 2016). These *Häufigkeitsverdichtungen* can either be an ongoing progress or take place with interruptions; they can occur either additively or cumulatively, either reversibly or irreversibly, either at a steady or an unsteady pace. Phases of deep change are driven by economic, social, technological, political and cultural processes at different speeds (Osterhammel, 2009; Braudel, 1985). We have seen huge changes within the energy sector in recent decades with regard to renewable energy production; these developments took place simultaneously in many places around the world. Currently there are some signs of similar transformations in the mobility sector as well. When it comes to the agricultural sector, or resource consumption, and the construction of new cities for the two to three billion additional people that will move to urban areas by 2050 worldwide, movement on the sustainability front has so far only been tentative and slow. Inequality is also on the rise in many countries, reducing people's development prospects and undermining social cohesion within many societies. The transformation towards sustainability is not an event, but rather a process characterized by asynchronisms.

In order to actually implement the Paris Agreement and the 2030 Agenda, it is necessary to scale up approaches for sustainable transformation, accelerate change processes and leverage dynamics of systemic change, for example with regard to deep decarbonization, a comprehensive circular economy and urban development that includes globally the lower 20 to 40% of urban dwellers. The transition from the "conditions of possibility" to a radical transformation is an ambitious one that needs to be properly shaped by drivers of change, but that could also fail and generate resistance and crises.

Common analyses and theories of social change (Chan, 2018; Messner, 2016; Geels, 2014; Kahneman, 2011; Appiah, 2010; Osterhammel, 2009; Leach et al., 2005; Mayntz, 2002) show that, for the transformation towards sustainability to succeed, there is a need for reorientation at the following levels:

4.4.1.1 Constellations of change agents

Past interests are always better organized than emerging future interests. We often fail to overcome climate-damaging production patterns and incentive systems due to social, political and power based path dependencies and well organized interests within the fossil fuel-based economy. Consequently, it is especially important to develop transformative partnerships and pioneer alliances for sustainable transformation. Cross-sectoral cooperation between change agents from the business and financial sector, research, policymaking, cultural and societal spheres brings about structural change and breaks up traditional networks representing past interests. As this report illustrates, many societies are on the move: new companies and business models are emerging, some of them in "old" sectors as well (such as automotive and energy companies); civil society actors, cities and science could become the driving force behind the transformation towards sustainability. Reform processes, such as the one at the World Bank, show how bastions of the "old economy" can become drivers of decarbonization (World Bank, 2015). Key actors, such as Governor of the Bank of England Mark Carney, are unlocking transformation prospects from the center of the global financial sector (Carney, 2018). The Paris Agreement has contributed to a multiplication of partnerships of climate change mitigation actors (Chan, 2018; WBGU, 2016).

4.4.1.2 Three motivating factors that create a willingness for transformation

Sustainability research has shown that tipping points could be triggered in our planetary system over the course of the 21st century, with far-reaching consequences for human civilization (Rockström et al., 2009). Social science studies outline how the erosion of societal cohesion can pose a risk to stability and security and trigger conflict (Alvaredo et al., 2018; World Bank, 2016). Scientific investigation has played a key role in highlighting future risks and establishing the need for a transformation towards sustainability. At the same time, such crisis scenarios can also leave people feeling paralyzed and give rise to a sense of helplessness, hopelessness and sometimes even anger. Attractive, hopeful, future-oriented and horizon-broadening narratives of opportunities and pathways to change can help people look to the future with confidence. Transformation (towards sustainability), that is, radical change, goes hand in hand with disruption, insecurity, unintended consequences, and events that cannot be planned and are often virtually impossible to anticipate. Equally, these costs and risks of transformation are some of the reasons people hold on to the established order and are resistant to sustainability reforms. Historically, people and societies only develop a willingness to change when there is a major crisis. European unification, the United Nations and the development of European welfare states were the consequences of two devastating world wars. The current crisis has a different shape. There is now a need in the 21st century to avoid reaching irreversible tipping points in our planetary system. When it comes to sustainability transformation, we need to move from a crisis mode of transformation to a preventive action mode. As such, it is necessary to generate, boost and spread motivation for the transformation towards sustainability. What drives people to work to bring about sustainable transformation? There are three main drivers of motivation that could play a key role here: 1) People respond to normative challenges and to developments that they consider to be unacceptable states of affairs – "How can we accept it that...?" is the initial impetus here. "How can we accept that this generation is destroying the environmental foundations for all future generations? How can we accept it that, despite all the prosperity we enjoy, a large proportion of the world's population still has no access to vital infrastructure?" "Moral revolutions" (Appiah, 2010) can serve as a starting point for transformation. 2) Fears about the largely unforeseeable consequences of deep changes (decarbonization of energy and mobility systems) can be allayed through the documentation of examples of successful transformation, thus, "showing what is possible...", e.g., the *Energiewende* (energy transition) in Germany, implementation of ambitious decarbonization plans in northern European cities, positive effects of resource-efficient business practices on labor markets in the United States and China, and an intelligent and generous refugee policy on the part of Uganda, a poor nation, since the outbreak of civil war in South Sudan. Demonstrating that transformations can succeed is a key driver for boosting motivation and bolstering courage for change. 3) The third type of motivational driver for difficult transformations is quite likely the most powerful (and renewable!) driver in the cultural evolution of humankind: imagination, creativity and the desire to create something new, beautiful, worthwhile and good. Time, and again visions, that is, positive narratives, of possible and better futures, have motivated people to push ahead with changes despite all the uncertainty they bring with them. Democracy, human rights, the end of slavery and welfare states are examples for such path breaking social innovations which changed the trajectories of human civilization. Currently, the 2030 Agenda is one such universal narrative of the possibility of a good life for many people – leave no one behind. It must be translated in many countries, regions, cities, communities and companies into diverse, attractive and practical future strategies which reflect the unique characteristics of the actors and communities concerned.

4.4.1.3 Four key normative innovations in the transition to sustainability

The transformation towards sustainability requires technological, institutional and economic innovations. However, for these to succeed, there needs to be a reinvention of people's normative horizons. Immanuel Kant described the essence of the enlightenment as a change in people's ways of thinking (*Veränderung der Denkungsart der Menschen*) – human rights, the rule of law and democracy that were "invented" and then spread successively to many societies. The transition to sustainability calls for similar normative innovations and reorientations, the four core elements of which are already found in the 2030 Agenda and the Paris Agreement: 1) the responsibility of the respective acting generations to prevent irreversible and dangerous changes in the planetary system (Rockström et al., 2009); 2) the linking of the concepts of national and global commons, which cannot take place without transnational reconciliation of interests, fairness and justice (Pogge and Mehta, 2016); 3) the acceptance of responsibility for the consequences of our current actions for many or (in cases e.g., of climate-induced sea level rises) even all future generations (WBGU, 2014); 4) the development of a global culture of cooperation which builds on the mobilization of the diversity of societies, their cultures, and the whole range of different normative systems of human communities as a resource for solving globally connected future problems (Zürn, 2018; Messner and Weinlich, 2016a; Tomasello, 2014). These core elements form the central points of reference of a new world view of global sustainable development. Anchoring them in our societies by means of education, knowledge diffusion, culture, joint action, standards, norms, political regimes and investments is a civilizational task.

4.4.1.4 Protection of the planetary system, efforts to strengthen social cohesion, and global cooperation are three linked concepts

Experience in many countries show that, without massive investment in the reduction of inequalities and the strengthening of social cohesion, it will not be possible to mobilize legitimation for structural reforms to mitigate climate change and protect other parts of the planetary system (WBGU, 2017). The social and environmental issues can only be solved through an integrated approach. At the same time, we see social justice and social cohesion within societies provide a basis not only for climate change mitigation and protection of the planetary system, but also for global cooperation (Messner and Weinlich, 2016b). If the social glue of societies crumbles and dangerous nationalist movements increase, then the willingness to engage in transnational cooperation for global sustainable development will decrease (Messner and Nakicenovic, 2017).

It becomes clear that the "conditions of possibility" (Kant) for mobilizing a major transformation towards sustainability and overcoming resistance to this transformation is a cultural and civilizational challenge for humankind, of an order similar to the major civilizational transformations that came in the wake of the Neolithic Revolution some 10,000 years ago and the Industrial Revolution, which began well over 200 years ago (WBGU, 2011).

Moreover, it is important to realize, that the sustainability transformations are taking place at a historic moment characterized by two other fundamental change dynamics that were still largely disregarded during the preparation and ratification of the 2030 Agenda and the Paris Agreement in 2015: "our county first" movements on the one hand and digital change processes on the other. The sustainability transformation can only succeed by simultaneously finding an appropriate response to these two major trends at the beginning of the 21st century.

4.4.2 How to deal with setbacks resulting from "our country first" movements

In many developing countries, emerging economies and OECD nations, nationalist, (in many cases) authoritarian, xenophobic, climate change-skeptical and anti-scientific movements and governments are becoming increasingly prominent. Not least in Europe, as well as at the transatlantic level, they represent a kind of "counter-transformation" to the sustainability transformation. Multilateral cooperation, climate change mitigation, universal norms and standards, and science are being called into question. While these movements address current challenges in the area of justice and the societal impacts of globalization, they do so in a way that is restricted to a nationalist, backwards-looking agenda (Messner, 2017).

There are no simple answers to such regressive trends, but there are four points to note here. First, the 2030 Agenda can offer part of the answer to this counter-transformation: More investment in fighting inequality and poverty, job creation and connecting economic and environmental modernization with social inclusion can help to reduce the insecurities and fears about the future that many people experience. Second, the confrontation between the concept of sustainability transformations and "our country first"– movements essentially comes down to a clash between fundamentally differing norm and value systems. The 2030 Agenda and the Paris Agreement are based on universal human rights and principles of global cooperation, transnational justice and responsibility, things which are being undermined and questioned by nationalist movements and governments. This conflict over the "defining cultures" of our societies and the prerogative of interpretation regarding the future needs to be resolved. Third, we should take account of the fact that the "program" for the sustainability transformation (e.g., scaling up of decarbonization efforts, acceleration of the transition to sustainability, disruption and systemic change as characteristics of transformative change) can itself give rise to and exacerbate insecurities and fears about the future among people who already feel threatened by the dynamics of globalization and technological change. Social policy and efforts to combat inequality will not suffice in and of themselves to curb nationalist backlashes. Disruptive change on the way to sustainability transformation can only succeed if at the same time confidence in the future grows, social cohesion is fostered, eroding identities are replaced by new local, national and transnational commonalities, cultures, and orientations, and if attractive future prospects arise. Strategies for transformation towards sustainability must take account of these insecurities that many people experience and find appropriate ways of responding to them, for example, through inclusive municipal policies, social, economic and political participation, educational offerings, the creation of development prospects for neglected regions, refugee integration initiatives which also help to improve living conditions for the vulnerable local population, international cooperation, and the promotion of clear standards and values, such as universal human rights, global responsibility and a global culture of cooperation.

Fourth, experiences in Europe between 1890 and 1910 (Kandel, 2012; Blom, 2008), the first phase of accelerated globalization, should offer warnings and lessons for the future. In many respects, today's dynamics are similar to those of that period from a structural point of view: Accelerated international economic activity, exploding trade, and profound structural change as a result of technological advances, profoundly changing labor markets, growing disparities between urban and rural areas, scientific breakthroughs (such as past ones in physics, microbiology, brain research and psychoanalysis and current ones in the areas of digitalization, nanotechnology and neurosciences) – and societies overwhelmed and stressed as a result of these accelerated structural change and modernization processes and lacking appropriate governance and normative frameworks needed to shape such ground-breaking innovations and trends. In many European countries and Germany in particular, the radical upheaval in the transition to the 20th century gave rise to political polarization, authoritarian nationalist movements and, ultimately, two devastating world wars. A look at history should provide us with a reminder and a warning in our converging global society at the beginning of the 21st century to fight centrifugal forces within our social contexts and work together to develop solutions to transnational interdependence problems instead of undermining national and international stability and security through nationalism.

4.4.3 The digital revolution – "What we need to talk about!"

The digital revolution, virtual realities, and (general purpose) artificial intelligence have recently entered the public discourse in many countries. Looking back, it is almost impossible to believe that digitalization barely featured in the 2030 Agenda or the Paris Agreement. It is increasingly clear that digital changes are becoming a key driving force in societal transformation (Tegmark, 2017; Domingos, 2015). The transformation towards sustainability must be linked with the digital transformation by gearing the opportunities and dynamics of the digital revolution to the goals of the 2030 Agenda and the Paris Agreement (Villani, 2018; WBGU, 2018). At the same time, the digital transformation will radically alter the sustainability paradigm itself. There are five correlations at the heart of the integration of the sustainability and digital transformations.

First, many studies (Acatech, 2016; Acatech, 2015) show that digital technologies can help to drive decarbonization (in the energy, mobility and industrial sectors), circular economy, dematerialization, resource and energy efficiency, and the monitoring and conservation of ecosystems at a much faster rate than would be possible without them. This does not happen in and of itself. There is a need for corresponding regulatory policies, which at present only exist in a small number of sectors and a limited number of countries.

Second, if it is not shaped appropriately and geared to the SDGs of the 2030 Agenda, then digitalization could multiply already existing problems in many societies: inequalities (e.g., in the labor market, in education systems and in the division of labor at international level) and centrifugal forces within society could increase further; economic and, by extension, political power could become more concentrated (see, for example, the significance of the "big five" - Amazon, Apple, Facebook, Google, Microsoft for the digital transformation); data sovereignty and civic rights could be restricted further and the monitoring of citizens and consumers ("social scoring") stepped up, especially in authoritarian societies; governance capacities of public organizations could erode further, since, for example, it is very difficult to tax digital business models in virtual environments. At the same time, digitalization could also help tackle these difficulties, and yet there are still very few instances of successful processes for shaping and governing digitalization around the world (WBGU, 2018). The accelerated technological developments threaten to overwhelm citizens and governments alike.

Third, policy makers, researchers, companies and civil society actors must multiply their efforts to understand and explain the multiple effects of digital change and anticipate far-reaching structural change in order to create a basis for shaping the digitalization process and gearing it to the 2030 Agenda and the Paris Agreement. Autonomous technical systems, based on learning machines and general purpose artificial intelligence, will fundamentally transform all areas of society and the economy in the near future (Villani, 2018; McKinsey Global Institute, 2017; Tegmark, 2017; Acatech, 2015; Brynjolfsson and McAfee, 2014; Barrat, 2013): Mobility, industrial sectors and production processes, value chains and the international division of labor, labor markets, financial systems, science and research, education, health care systems, political decision-making processes, and the judiciary. By processing enormous volumes of data, AI-based machinery will steer production processes, traffic, and financial flows, revolutionize medical diagnostics, change the way insurance companies make decisions, make decision documents available to parliaments and governments, and generate behavioral forecasts for individuals and groups (Domingos, 2015). During the last two to three million years, human civilization has been based on human intelligence – human intelligence has had no rival. Now it is being supplemented by artificial intelligence, which, in some areas at least, is far superior to human analytical capabilities. Linking human and artificial intelligence and creating "meaningful artificial intelligence" geared to the goals of sustainable human development (Villani, 2018) is set to become a major task for humanity in the first half of the 21st century. How can we reduce the error rate of (globally) connected technical infrastructures and make it more robust? How can our legal systems keep pace with accelerated technological change? How can the unintended effects of private investment in the development of self-learning technical systems and virtual environments be understood by citizens and governments, and be geared to and shaped in accordance with our standards systems? How can prosperity be multiplied through automation and the principle of leaving no one behind observed at the same time? What are the implications of the technological revolution for the poorest developing countries? Where is the line when it comes to using technology to alter, improve and manipulate people's cognitive, physical and emotional capacities? What ethical guardrails should be put in place in the discussion about the transformation of humans and human enhancement? These questions illustrate the magnitude of the formative tasks associated with the digital transformation in the context of building a sustainable global economy.

Fourth, technological breakthroughs offer mind-blowing potential for human civilization, provided the digitalization process and associated technologies are shaped appropriately: the expected explosion of knowledge, possibilities for transnational networks in virtual environments as the basis for the establishment of transnational cultures of cooperation, opportunities for comprehensively monitoring and, by extension, conserving the planetary system, and the multiplication of options for horizontal participation on the part of many people as a result of digital networking. The printing press, which from an artificial intelligence perspective may appear to be a rather small step in human development, was the innovation that made the enlightenment, scientific investigation, democracy and the industrial revolution possible in the first place. Might we see a new kind of Enlightenment as a result of combining artificial and human intelligence with human empathy and social intelligence? How can we exploit the potential of digitalization to tackle the major challenges facing humanity in the 21st century – and avoid the daunting risks of accelerating technological changes running out of control?

Fifth, we will only be able to exploit the opportunities of digitalization, virtual realities, and artificial intelligence, and curb their potential risks and link the digital and the sustainability transformation if the digital and sustainability research communities converge, something which is still a long way off right now. Connecting the greatest innovative dynamics in human history with the major transformation towards sustainability, in order to stabilize the planet and enable a good life for a nine to ten billion civilization in the 21st century will require tremendous efforts, swift actions, institutional changes, huge investments, patience and a clear normative framework (WBGU, 2019).

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1. Transformation towards a sustainable future is possible but ambitious action is needed now!
2. Six transformations are necessary to achieve the SDGs!
3. Attaining the SDGs in a resilient and lasting way, requires vigorous action now, and a people and planet focus beyond 2030!
4. As everything is integrated in the connected world, the grand transformation requires a holistic perspective!
5. Transformational change is needed but to succeed we must take along winners and losers!
6. The world is at crossroads as we are currently experiencing signs of a counter-transformation!
7. A central element of the sustainability transformation is effective and inclusive governance!
8. Think globally, act locally! Think long-term, act now! It is all a matter of scale!