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Six Transformations to achieve the Sustainable Development Goals

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The Sustainable Development Goals (SDGs) and the Paris Agreement on Climate Change call for deep transformations in every country that will require complementary actions by governments, civil society, science and business. Yet stakeholders lack a shared understanding of how the 17 SDGs can be operationalized. Drawing on earlier work by The World in 2050 initiative, we introduce six SDG Transformations as modular building-blocks of SDG achievement: (1) education, gender and inequality; (2) health, well-being and demography; (3) energy decarbonization and sustainable industry; (4) sustainable food, land, water and oceans; (5) sustainable cities and communities; and (6) digital revolution for sustainable development. Each Transformation identifies priority investments and regulatory challenges, calling for actions by well-defined parts of government working with business and civil society. Transformations may therefore be operationalized within the structures of government while respecting the strong interdependencies across the 17 SDGs. We also outline an action agenda for science to provide the knowledge required for designing, implementing and monitoring the SDG Transformations.

By adopting the 2030 Agenda with its 17 SDGs (Supplementary Section 1) and the Paris Agreement, member states of the United Nations have created a framework for national action and global cooperation on sustainable development[1]. The SDGs focus on time-bound targets for Prosperity, People, Planet, Peace and Partnership—known as the five Ps. The Paris Agreement commits countries to achieve net-zero greenhouse-gas emissions by the middle of the century[2]. SDG 13 on climate change links to the Paris Agreement, noting that the UN Framework Convention on Climate Change "is the primary international, intergovernmental forum for negotiating the global response to climate change"[3].

Evidence suggests that international development goals, such as those around public health, can accelerate progress towards complex development goals[4], but achieving the SDGs will require deep, structural changes across all sectors in society. This raises the critical question of how strategies to achieve the 17 SDGs can be organized.

Several authors have shown that SDG outcomes, including the objectives of the Paris Agreement, are interdependent[1,5,6] with complex coupling between human, technical and natural systems. Yet the available studies do not emphasize how the implementation of the SDGs should be organized.

To help fill these gaps, we outline a systemic policy approach to achieve each SDG (Supplementary Section 4). As with the much simpler Millennium Development Goals[7], many policy interventions (such as public investments and regulations) are needed to achieve each SDG, and each intervention generally contributes to several goals. Governments need a strategy to design and implement key interventions. Building on The World in 2050[1] and earlier work (Supplementary Section 2), we propose six Transformations to organize SDG interventions through a semi-modular action agenda that can be designed by discrete, yet interacting, components of government. Each Transformation engages a different subset of business and civil society, facilitating targeted problem-solving, clear communication and the mobilization of stakeholders[8]. We describe how the Transformations can be operationalized with a focus on government action and conclude with an action agenda for science.

Organizing the implementation of the 17 SDGs

We first consider which key interventions are necessary to achieve the SDG outcomes (Table 1 and Supplementary Section 4) and how their implementation might be organized into a limited set of six Transformations. To simplify the discussion of interlinkages between interventions and SDGs, we identify intermediate outputs generated by combinations of interventions, which in turn contribute to the achievement of each SDG. Drawing on established methodologies[5,6], we describe the strength of the relationship between intermediate outputs and each SDG on a four-point scale: 3, directly targets the SDG; 2, reinforces the SDG; 1, enables the SDG; and 0, has no interaction with the SDG (Supplementary Section 4).

Table 1 presents no negative relationships between intermediate outputs and SDG outcomes since major trade-offs, as identified in the literature[5,6], are addressed in three ways. First, some trade-offs (between agricultural production and biodiversity loss, for example) are addressed through systems-based approaches that combine potentially antagonistic interventions inside a Transformation. Second, key interventions are designed to be consistent with the leave-no-one-behind principle (Box 1) to ensure that investments in services, infrastructure and technologies promote equity. Third, natural resource trade-offs are addressed through the principle of circularity and decoupling within a stable Earth system (Box 2).

Our proposal to organize SDG interventions into six discrete SDG Transformations (Fig. 1) builds on The World in 2050[1] and categorizes using five principal characteristics (Supplementary Section 3). The Transformations must be: (1) mutually exclusive and collectively exhaustive; (2) systems-based; (3) aligned with government organization; (4) easily communicable; (5) few in number.

Each SDG Transformation describes a major change in societal structure (economic, political, technological and social) to achieve

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long-term sustainable development. The six Transformations are necessary for achieving the SDGs and the objectives of the Paris Agreement (Supplementary Section 4). Each contributes to multiple SDGs (Fig. 2). Dropping any of them would make it impossible to achieve the SDGs. The Transformations work at global, regional and national scales. They need to be adapted to country contexts, such as levels of development, natural resource base, ecosystem challenges and structures of governance.

Key SDG interventions by Transformations

We describe below the rationale for each Transformation, key interventions and how they generate intermediate outputs (Table 1). Issues arising from implementation and the contributions each Transformation makes towards meeting the SDGs are also explored. Supplementary Section 4 provides further details.

Transformation 1. Education builds human capital, which in turn promotes economic growth[9], the elimination of extreme poverty, decent work, and overcoming gender and other inequalities[10,11]. The first Transformation comprises three sets of interventions to promote education and gender equality and to lower inequalities.

First, countries need to expand and transform education systems. Early childhood development boosts the cognitive and emotional development of children with persistent effects into adulthood, but has been underinvested in many countries, including high-income economies[12]. Universal quality primary and secondary school education is the backbone of education systems. It requires enhanced teacher training, curriculum development and continuous evaluation of learning outcomes[10,13] as offered by the Organisation for Economic Co-operation and Development's Programme for International Student Assessment. Vocational training, school-to-work programs and higher education are underdeveloped in most countries, despite the fact that they improve the school-to-work transition, increase lifetime earnings and reduce inequalities[11]. Together, these interventions build human capital, which directly targets SDGs 4 (education), 5 (gender equality) and 10 (reduced inequalities).

Second, to further reduce inequalities, countries need to expand social safety nets[14,15]. These need to be complemented by anti-discrimination measures, improved labour standards and measures to end all forms of modern slavery, trafficking and child labour[16].

Finally, to promote economic growth (which can contribute to lowering inequalities; Supplementary Section 4), most countries need to boost innovation and ensure diffusion from research and development[17]. The adoption of new technologies can be accelerated through tertiary education; national science funding mechanisms and science advisory bodies; innovation hubs; and the promotion of entrepreneurship through public–private financing mechanisms and incubators[18].

The interventions under this Transformation are synergistic with no major trade-offs, provided that the leave-no-one-behind principle is applied. The Transformation will require integrated design and implementation of interventions through close coordination between ministries of education, science and technology, and social affairs, or their equivalents.

Transformation 2. This Transformation promotes key investments in health and well-being. Design and implementation will be led by health ministries in coordination with other ministries, such as labour and industry. As with Transformation 1, the key interventions under this Transformation are synergistic without any major trade-offs, provided that the leave-no-one-behind principle is applied. Interventions under other Transformations, particularly relating to environmental health and healthy behaviours, reinforce health outcomes and well-being[19–22].

The principal intermediate output is universal health coverage. It requires a publicly financed health system that integrates prevention, therapeutic and palliative services; integrated information systems; and disease surveillance and control[19]. Health systems need to focus on primary healthcare and offer interventions for maternal, newborn and child health; effective prevention and treatment of infectious diseases; and non-communicable disease control, including mental health and basic surgery[19]. In combination with improved girls' education and gender equality, investments in child health and sexual and reproductive health will accelerate the voluntary transition towards low fertility rates[10,23]. Community health programmes can improve health outcomes significantly[19].

Health interventions outside the health sector can improve the social determinants of health. They include policies and metrics to raise well-being and quality of life. Changes to social norms and behaviours promote healthy lifestyles through better hygiene; lower consumption of tobacco, alcohol and other harmful substances; and abstaining from risky behaviour (for example, practicing safe sex prevents the spread of sexually transmitted diseases). Countries should consider subjective well-being in policy design[22], improve product design and labour standards to reduce accidents; and lower traffic deaths. Healthy diets, a critical determinant of health outcomes[24,25], are covered under Transformation 4, and Transformation 5 includes measures to curb the pollution of water and air.

Transformation 3. This Transformation aims to ensure universal access to modern energy sources[26], decarbonize the energy system by mid-century in line with the Paris Agreement[2] and reduce industrial pollution of the soil, water and air[27,28]. The implementation of this Transformation requires close coordination among several government ministries, including buildings and construction, energy, environment and transport. Interventions are synergistic, but trade-offs can arise from poor design.

Ensuring access to modern energy services translates to providing access to electricity to some 1.1 billion people through grid extensions or microgrids, as well as providing access to modern fuels for cooking and heating to the 2.8 billion who lack this today[26].

Decarbonizing energy systems requires integrated approaches across power generation, transmission, buildings, transport and industry[29–31], which fall into three distinct areas[32]. The first covers the decarbonization of electricity generation by shifting from fossil fuels to zero-carbon sources, including wind, solar, hydro, geothermal and tidal energy, among others. Some countries may also expand nuclear power or consider continued fossil-fuel use with carbon capture and storage. Smart-grid management and long-distance power transmission can address intermittency, reduce electricity storage needs and increase the efficiency of power grids[29]. Second, countries need to improve energy efficiency in final energy use, including transport, heating and cooling of buildings, industrial energy use and household appliances[29]. The third comprises the electrification of current uses of fossil fuels outside of power generation, such as the internal combustion engine, through electric or hydrogen vehicles, boilers and heaters, and various industrial processes such as steel and cement production. Biofuels and biomass can provide clean thermal energy, but their use must ensure consistency with food security, biodiversity conservation and other SDGs[33].

A related set of SDG interventions focuses on managing industrial pollutants of the air, water and land, including through circularity (Box 2). Key industrial pollutants include methane, nitrous oxides and sulfur dioxide, as well as organic and other inorganic pollutants and plastics. Water and waste management, life-cycle approaches, and other tools of circular economy, can increase resource-use efficiency and lower pollution[28,34].

The design and implementation of this Transformation are complex. One trade-off can arise from neglecting to pursue energy access and affordability in parallel to decarbonization. Such a failure may generate public resistance to climate policies[35]. Similarly,

Table 1 | How SDG Transformations contribute to the achievement of the SDGs

Transformation	Principal line ministries involved in Transformations	SDG interventions	Intermediate outputs	Relationship with specific SDGs															
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	Education Science and technology Family and social affairs	Early childhood development	Education and human capital	2	1	2	3	3	1	1	2	2	2	1	1	1	1	1	1	1
		Primary and secondary education																		
		Vocational training and higher education																		
		Social protection system and labour standards	Decent work and income support to vulnerable groups	3	3	2	1	2	1	2	3	1	3	1	1	2	2	2	1	0
		Research and development	Innovation	1	2	1	1	1	1	2	2	3	1	1	2	2	1	1	1	2
2	Health	Universal health coverage	Public health services	2	3	3	2	3	0	0	2	1	2	1	1	0	0	0	1	0
		Healthy behaviours and social determinants of health and well-being																		
3	Buildings/construction Energy Environment Transport	Access to clean energy	Energy access for all	2	1	2	2	2	1	3	2	3	2	3	2	3	1	2	1	0
		Zero-carbon electricity generation	Energy decarbonization	1	2	2	0	1	2	3	2	2	2	2	3	3	2	2	2	1
		Energy efficiency																		
		Electrification and zero-carbon fuels																		
		Curbing pollution	Clean air and water	1	1	3	1	1	3	1	2	1	1	3	3	2	3	3	1	1
4	Agriculture Environment Fisheries and marine resources Forestry Health Water and natural resources	Efficient and resilient agricultural systems and fisheries that support healthy diets and farm livelihoods	Sustainable land-use, oceans, and food systems	2	3	3	1	2	3	1	2	1	2	2	3	3	3	3	1	1
		Protection of terrestrial and marine biodiversity, including forests																		
		Healthy food promotion and regulation																		
		Trade and supply chains consistent with sustainable development																		
		Integrated land-use and water management																		
5	Transport Urban development Water and sanitation	Urban access to water, sanitation and waste management	Transport, water and sanitation infrastructure services	2	2	2	2	2	3	1	2	3	2	3	3	2	2	2	0	0
		Sustainable mobility and transport networks																		
		More compact settlements																		
		Urban adaptation and resilience	Urban resilience	1	1	1	1	1	2	1	1	2	2	3	1	3	0	0	1	0

Continued

Table 1 | How SDG Transformations contribute to the achievement of the SDGs (continued)

Transformation	Principal line ministries involved in Transformations	SDG interventions	Intermediate outputs	Relationship with specific SDGs															
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
6	Science and technology Telecommunications	Universal broadband and information-technology infrastructure Digital inclusion, skills, privacy protection and universal identity Mobilizing digital technologies to achieve all SDGs	Digital technologies and infrastructure	2	2	2	2	1	1	2	2	3	2	2	2	2	1	1	1	2

Each Transformation comprises key SDG interventions that together generate intermediate outputs, which serve as inputs into achieving the SDGs. The relationships with SDG outcomes are described using a four-point scale: 3, intermediate outputs target directly SDG outcomes; 2, reinforce the SDGs; 1, enable the SDGs; and 0, do not interact with the SDGs. Table 1 also lists line ministries that would oversee the implementation of each Transformation (excluding central coordinating agencies, such as project-management offices, planning and finance). See Supplementary Section 4 for more information.

Box 1 | The leave-no-one-behind principle

The 2030 Agenda pledges that no one will be left behind in implementing the SDGs. This principle of equity and fairness aims to overcome inequalities and discrimination by gender, race, social status or other qualifiers, which result from a range of factors including power dynamics, discrimination, poor system design and insufficient financing[14,62]. The SDGs may not be able to overcome all drivers of inequality, but by underpinning the design, implementation and monitoring of all six Transformations with the leave-no-one-behind principle, substantial progress could be made. For example, health outcomes are undermined by inequalities, so health strategies must address the needs of the most vulnerable[19,20]. Similar considerations apply in education[10,12,13]. Recent protests against the social costs of strategies to decarbonize energy systems in France, Germany and other countries highlight that the energy Transformation can only succeed if it is underpinned by the leave-no-one-behind principle. Strategies to transform cities and human communities require participatory urban planning to identify and address the needs of the poorest[49]. As described under Transformation 6, the digital revolution holds tremendous promise for better meeting the needs of the extremely poor, but unless well managed it threatens jobs, undermines governance capabilities and may exacerbate inequalities[15,54].

Box 2 | The principle of circularity and decoupling

To achieve the SDGs, countries must change patterns of consumption and production to decouple human well-being from environmental degradation through circularity that promotes reuse and recycling of materials[79], among other strategies. Circularity and decoupling without lowering human well-being must underlie all SDG Transformations. The most important decoupling is decarbonization, that is, the reduction of net greenhouse-gas emissions to zero by mid-century[2]. Countries must also make material systems sustainable[80] and dissociate the net release of nitrogen, phosphorous, chemicals, plastics, particulates and other pollutants from human well-being[40]. Similarly, the use of freshwater, land and non-renewable resources needs to be decoupled from social and economic progress[34]. Life-cycle approaches to electric vehicles and other key energy technologies are critical for reducing the resource intensity of Transformation 3 to decarbonize energy and make industry sustainable[29]. In agriculture and food systems (Transformation 4), circularity is widely applied—particularly for livestock management[81] and food loss and waste[82]. Cities (Transformation 5) also need to adopt principles of circularity in the design and management of resource flows[49]. The digital revolution (Transformation 6) is an important enabler of circularity and decoupling.

while improving air quality and reducing greenhouse-gas emissions are generally complementary, coal-to-gas and similar technologies may improve air quality but increase greenhouse-gas emissions[27]. Moreover, a more efficient and low-cost energy system may generate a substantial rebound effect, in which demand growth compensates for increased resource-use efficiency. The use of other scarce resources, such as rare metals, might rise, with serious environmental and social consequences. Anticipating and addressing these trade-offs will require sound accounting frameworks, applying the principles of leave no one behind (Box 1) and circularity and decoupling (Box 2) and social activism (addressed below).

Transformation 4. Today, land-use and food systems lead to persistent hunger, malnutrition and obesity[24,25]. They account for a quarter of greenhouse-gas emissions[2], over 90% of scarcity-weighted water use[36], most losses of biodiversity[37,38], overexploitation of fisheries[39], eutrophication through nutrient overload[40] and pollution of water and air[41]. At the same time, food systems are highly vulnerable to climate change and land degradation[2]. Integrated strategies are needed to make food systems, land-use and oceans sustainable and healthy for people.

This Transformation exhibits the highest potential for trade-offs across interventions. Increases in agricultural production may exacerbate biodiversity loss and water scarcity. Rising incomes around the world will add to the pressure on food systems, unless diets become healthier and more environmentally sustainable. As a result, the interventions must be pursued in an integrated manner[42] with attention to the principles of leave no one behind (Box 1) and circularity and decoupling (Box 2). Strategies should be designed and implemented by ministries of agriculture and forestry, environment, water and natural resources, fisheries and marine resources, and health. Most governments will need to strengthen coordination mechanisms across these ministries to anticipate and manage trade-offs.

Fig. 1 | Six SDG Transformations. Each Transformation describes a major change in the organization of societal, political and economic activities that transforms resource use, institutions, technologies and social relations to achieve key SDG outcomes (represented by the SDG wheel in the centre). Figure adapted from ref. [1], TWI2050; SDG colour wheel courtesy of UN/SDG.

The first intervention area focuses on efficient and resilient agricultural systems and fisheries that support livelihoods. Major increases are needed in yields and resource-use efficiency in terms of nutrients, water, greenhouse-gas emissions and chemicals[36,37], and in the reduction of post-harvest losses. This will in turn require context-specific strategies for major cropping systems, livestock, aquaculture, fisheries, forestry and biofuel production. In parallel, agricultural practices must better protect biodiversity through intercropping, agroforestry, biosphere reserves and judicious use of chemicals[43]. Improved management practices are needed for coastal and high seas fisheries to curb overfishing and maintain yields[39,44].

Second, forests, soils, peat lands, wetlands, savannahs, coastal marine areas and other ecosystems must be conserved and restored[38]. Conservation measures must be designed and implemented in cooperation with local communities. The same applies to large-scale restoration programmes and measures to increase soil fertility and capture more carbon in the biosphere, as illustrated by experiences in China[45].

Third, food insecurity and hunger need to be curbed through complementary safety nets and targeted interventions[46]. Consumer demand must shift towards healthier diets, including a move away from highly processed food and red meat, as well as reduced losses and wastage along food supply chains[24,25,36].

International supply chains must ensure sustainable resource use and curtail pollution. Importing countries need to consider the environmental impact of imports in exporting countries, in particular, and stop the trade in endangered species. International investments in agricultural land must be carefully managed to ensure long-term sustainability and acceptability to the local population. Finally, countries require strategic land-use, ocean-use and water-management approaches to help manage competing claims on land and water for food production, urban development, industry and mining, ecosystem management, carbon sequestration and biodiversity conservation[42], as well as on the ocean for transport, food production, energy harvesting, mining and tourism[47].

Transformation 5. Cities and other urban areas (hereafter referred to as cities) are home to around 55% of humanity and 70% of global economic output. By 2050, these shares will increase to 70 and 85%, respectively[48]. Cities are particularly vulnerable to climate change, but most cities are far from meeting the triple objective of being economically productive, socially inclusive and environmentally sustainable[2,49,50]. Almost one-third of urban dwellers live in informal settlements[51]. Many villages and small towns lack access to water, sanitation, transport[26,52] and energy (Transformation 4).

A first focus of this Transformation is ensuring access to the water supply, sanitation and appropriate sewage and waste disposal in urban and rural areas. An estimated 1.2 billion people lack access to safely managed drinking-water services, and 2.4 billion people do not have access to safely managed sanitation[53]. Investments in water supply and sanitation are synergistic with measures to address water scarcity that align water demand from agriculture with sustainable supply (Transformation 4). Recycling and sustainable waste-management practices are also critical (Box 2).

Sustainable and efficient mobility is a second priority. This includes infrastructure for roads, railways and ports, as well as

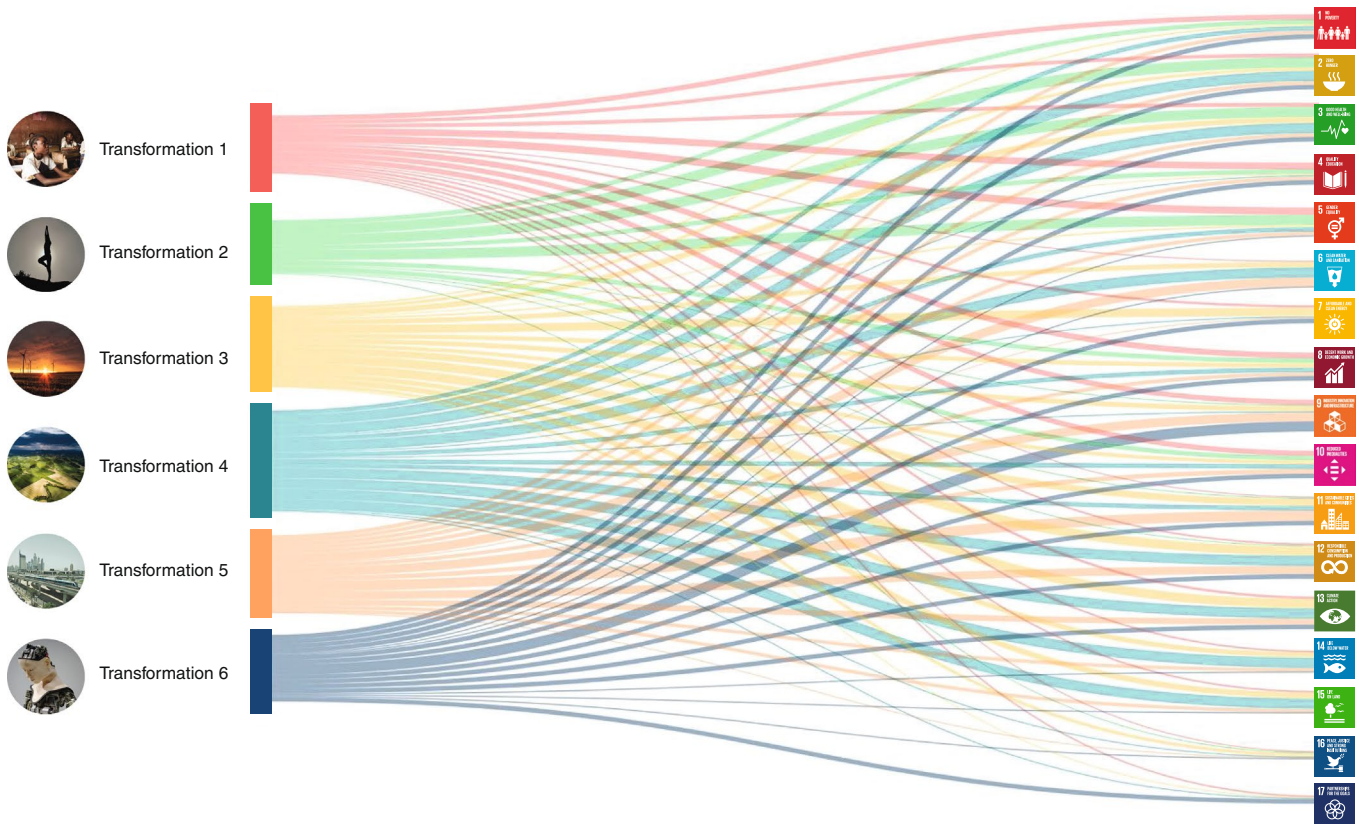

Fig. 2 | Contribution of each SDG Transformation towards the 17 SDGs. Sankey diagram illustrating the relationships between each Transformation and the SDGs (Table 1). The thicker the line, the greater the contribution of that Transformation to meeting the SDGs (see Supplementary Section 5 for methods). SDG icons courtesy of UN/SDG.

public transport systems and ride-sharing. Infrastructure should be deployed according to participatory and inclusive urban planning that takes into account expected population growth[49] and balances trade-offs between infrastructure services and other policy objectives, as well as competing interests within cities. Particular attention must be paid to reducing air pollution from transport[27] and ensuring the long-term sustainability of transport.

Third, cities need to promote more compact, safe and healthy settlements to accommodate rising urban populations, enhance resource-use efficiency (Box 2) and avoid excessive land conversion (Transformation 4). This will require adequate green spaces, infrastructure for cycling and walking, and other interventions to increase resource-use efficiency and quality of life[46].

Cities also need to enhance resilience against climate change and extreme weather events, including more heat waves, droughts, flooding and enhanced disease transmission[2,50]. This will require participatory and inclusive urban planning to address difficult trade-offs, such as resettlement[49–51].

Organizing this Transformation is particularly complex, owing to the large number of stakeholders involved and the distribution of responsibilities between national and local levels of government. Ministries of transport, water and sanitation, and urban development will play central roles. But most importantly, cities require competent and adequately resourced local authorities that can pursue integrated strategies and ensure participatory design[46].

Transformation 6. Artificial intelligence and other digital technologies—sometimes referred to as the Fourth Industrial Revolution—are disrupting nearly every sector of the economy, including agriculture (precision agriculture), mining (autonomous vehicles), manufacturing (robotics), retail (e-commerce), finance (e-payments and trading strategies), media (social networks), health (diagnostics and telemedicine), education (online learning), public administration (e-governance and e-voting) and science and technology. Digital technologies can raise productivity, lower production costs, reduce emissions, expand access, reduce resource intensity of production processes, improve matching in markets, enable the use of big data and make public services more readily available. They can also improve resource efficiencies, support the circular economy (Box 2), enable zero-carbon energy systems, help monitor and protect ecosystems, and assume other critical roles in support of the SDGs[1,54,55].

Yet there are risks and downsides that countries must identify and tackle through integrated strategies and a focus on the leave-no-one-behind principle (Box 1). Perhaps the most feared risk is the loss of jobs, particularly for lower-skilled workers, and the shift of income distribution from labour to capital[15]. While new jobs might replace existing ones, these new jobs may come with lower real earnings and worse working conditions[15]. Base erosion, profit shifting and the concentration of industries threaten to undermine countries' tax bases[56]. Other threats from the digital revolution include the theft of digital identities, invasion of privacy by governments or businesses, discrimination based on personal data, monopoly positions due to control of big data, challenges to deliberative decision-making processes, cyber warfare, hacking of election data and the manipulation of social media.

The sixth SDG Transformation calls for a comprehensive set of regulatory standards, physical infrastructure and digital systems to capture the benefits of the digital revolution for the SDGs while avoiding the many potential pitfalls. It comprises four sets of

interventions. First, universal access to high-quality, low-cost mobile broadband. Second, measures to promote digital inclusion, skills, privacy protection and universal identity. These include the digitization of government facilities, universal public online identity for official purposes, income redistribution to address income inequalities, tax and regulatory systems to avoid the monopolization of Internet services and big data, online data governance and interoperability provisions, and democratic oversight of cutting-edge technologies[54]. Third, countries need to harness the digital revolution to attain SDGs, including through the digitization of healthcare and education, online finance and payments, and supporting public goods[57]. Fourth, public institutions need to be strengthened to govern and shape digital innovations towards sustainable development. Technology missions, as considered below, can harness technologies to tackle implementation challenges across the six SDG Transformations.

This Transformation requires leadership from ministries of science and technology as well as telecommunications. They must coordinate closely with other parts of government and stakeholders—particularly through public–private partnerships—to anticipate and manage the deep societal changes that are both triggered by and needed for the digital revolution, particularly regarding inequalities, the future of work and how artificial intelligence may affect societal decision making[58].

Implementing the six Transformations

The six Transformations require deep, deliberate, long-term structural changes in resource use, infrastructure, institutions, technologies and social relations that must be undertaken in a short period of time. Previous societal transformations, such as the industrialization in nineteenth-century Europe, were spurred by technological advances (for example, the steam engine and railroad) and were largely undirected, although the rollout of technologies often occurred with government support. In the twentieth century, technologies such as semiconductors, the Internet and the Global Positioning System were promoted through directed innovation to meet military aims[59]. SDG Transformations must be directed to meet time-bound, quantitative targets, such as net-zero carbon emissions by mid-century.

The six Transformations can be designed and directed in several ways. First, they must meet the standards of technical feasibility. Second, the Transformations need to address and resolve trade-offs. Third, they will be financed through a combination of public and private financing[60]. Fourth, they need to accelerate development and deployment of new technologies. Fifth, policy coherence is needed across branches of government (horizontal), between levels of government (vertical) and through time (temporal)[61] to manage trade-offs and ensure timely implementation. Sixth, business can provide co-financing and drive many of the organizational and technological changes required, so each Transformation must engage the business community through a coherent set of policies, market incentives and regulations. Finally, the transformations require civil-society engagement and public debates about sustainable development pathways.

Drawing on the transformation literature[62–64] as well as our own research and experiences in advising governments, we propose four major governance mechanisms to design and operationalize the Transformations. Since the SDG Transformations are without historic precedent, any description of transformative governance mechanisms is necessarily exploratory and subject to later refinements through 'learning by doing'.

Goal-based design and technology missions. Two design mechanisms can support long-term SDG Transformations in every country. First, governments (with support from science, engineering and public policy disciplines) need to set medium-term targets with time horizons of 10–30 years (that is, 2030 for the SDGs and 2050 for the Paris Agreement) and develop detailed policy pathways for achieving these targets. This requires working backwards from these time-bound targets to identify the systems design, investment trajectories and technologies that can deliver the long-term goals[1,8,31,42]. In some cases, the pathways can be set up as a formal multi-dimensional, multi-period, nonlinear programming problem (for example, how to achieve decarbonization at minimum cost). Pathways should provide insights on time-bound technology benchmarks, such as the phase-out of the internal combustion engine around 2030, that help educate the public about the Transformation and can guide investment decisions by industry[8,30,31]. Given the complexity of the Transformations and the need for broad societal buy-in, this design process must be transparent and participatory.

The health sector shows how to use pathways as a method for complex problem solving[8]. Pathways synthesize our understanding of how multidimensional goals and targets can be achieved, highlight knowledge gaps, focus on systems and technologies, and enable stakeholder engagement.

The balance between rigorous technical pathway analyses and stakeholder engagement is critical, as illustrated by California's experience in operationalizing the energy transition. The State asked leading engineers to develop technology pathways for deep decarbonization using high-resolution, bottom-up models of the energy systems. Results were then discussed with energy utilities, the finance sector, trade unions and other stakeholders. Each group provided new insights and identified shortcomings in the analyses and recommendations, which were incorporated into improved pathways. This yielded better pathways and societal acceptance[65]. Potential losers in the transition were identified early on, and strategies were developed to compensate them and ease the move into new jobs. Europe has followed a similar analytical process[66], although with less stakeholder engagement and public discussion.

The second mechanism for operationalizing long-term transformations is missions for directed technological change. These promote problem solving by combining top-down visions with bottom-up experimentation across many sectors[18]. Historic examples include the United States' 'Moon Shot', the sequencing of the human genome, the development of the Internet and the promotion of renewable energy. Each mission requires strategic decisions on how general-purpose technologies (such as Internet-based applications and battery storage for intermittent renewable energy) can create opportunities across sectors; finance, regulations and standards to promote innovation and investment; and the use of government procurement to scale up new technologies. The more ambitious and inspirational missions are, the stronger their ability to draw in different forms of private finance[18]. Each SDG Transformation requires such missions as frameworks for accelerating innovation, technology development and deployment.

Goal-based organization of government and financing. Next, government organization, budgetary frameworks and financing must be aligned with long-term pathways. Most countries will need to increase domestic resource mobilization, and low-income developing countries will require increased international financial assistance[60]. To mobilize private financing and direct it towards each Transformation, governments can use corrective pricing through taxes, charges or tradable permits, or direct regulation and mandates, such as land/ocean-use planning, building codes or bans on hazardous products.

To organize around the six Transformations, governments will require cabinet-wide coordination, typically in the office of the president or prime minister. Sub-cabinet groups can be organized around each Transformation. Such structured approaches are generally lacking at present, including in most advanced economies[67].

The Transformations can only succeed if they enjoy societal legitimacy, so political processes should engage the public in participatory decision-making and promote transparency and accountability. New ways for decision-making to engage social movements—such as those around decarbonization—are crucial. When policy challenges are complex, politically charged and have a long time horizon, countries may establish an independent agency or commission to bring about long-term systems change, subject to general democratic scrutiny by elected officials[68].

Social activism to change norms and behaviours. The six Transformations require fundamental changes in norms, belief systems and cognitive heuristics. Large-scale shifts in perspective, normative and cognitive innovations (for example, from linear growth to circularity; taking responsibility for the global commons; and global fairness as a condition for human survival) drive transformations and ensure their public acceptance[69,70]. Such changes cannot be driven solely by governments and emerge instead from dialogues and learning processes between stakeholders. They can be supported by governments, through transdisciplinary research and education. Large-scale societal change is often achieved first in the hearts and minds of the people, and only afterwards accepted in legislation and economic policies. Social movements, public activism and awareness campaigns should explain the ethics of sustainable development, promote grass-roots activism and community participation, shareholder activism and fair-trade consumer movements. Moral leaders should expound the ethical teachings of the world's major religions in the context of sustainable development, such as Pope Francis' encyclical *Laudato Si'*[71].

Diplomacy and international cooperation for peace, finance and partnerships. International diplomacy and law can promote the six Transformations in several ways. First, the most essential foundation of sustainable development is peace, which requires international cooperation to resolve disputes through norms and institutions, support peacekeeping and curb meddling in other countries' affairs[72]. Second, achieving the SDGs in low-income developing countries will require substantial and greatly increased development financing, including official development assistance, to close SDG financing gaps[60]. Third, international collaboration is needed to combat crime, reduce sexual violence and end human trafficking, which has become a major driver of modern forms of slavery. Fourth, a fair, rules-based trade system would support economic development in rich and poor countries alike. It would promote export-led development, which has driven unprecedented poverty reduction over the past decades, particularly in Asia. Finally, international cooperation (for example, through treaties, technical working groups, regional and international development banks, city alliances or UN agencies) is required to tackle air pollution, biodiversity loss, climate change, freshwater scarcity, ocean degradation and other environmental challenges[73].

An action agenda for science

The six SDG Transformations provide a framework for mobilizing governments, business and civil society around targeted problem-solving and SDG implementation. A shared framework is critical as different ways of framing SDG implementation lead to confusion and dissipate energy. We are therefore very encouraged that international business organizations such as the World Business Council for Sustainable Development and the World Benchmarking Alliance already embrace the concept of SDG Transformations.

Important knowledge gaps exist in designing pathways and strategies for each Transformation, implementing them and monitoring results. The scientific community should embrace the following four-point action agenda.

Capacity for designing transformations. Sophisticated tools are needed to design pathways for the six Transformations. These pathways require the integrated efforts of scientists, engineers and policy specialists. Such tools have been developed in the health sector[7] and are now routinely used for universal health coverage strategies[19]. Tools also exist for education[74], but are less commonly used at the country level. The Food, Agriculture, Biodiversity, Land-Use, and Energy (FABLE) Pathways Consortium, which operates as part of the Food and Land-Use Coalition (www.foodandlandusecoalition.org), is a global network of country teams that collaborate around building new capacity for data integration and spatially explicit pathways towards sustainable land-use and food systems[42]. So far 20 country teams participate in the FABLE initiative. The Deep Decarbonization Pathways Project[8,31] has been building capacity for the design of national energy decarbonization pathways, complementing regional and global pathways. The TWI2050 Initiative (http://twi2050.org/) uses integrated assessment models for pathways that cover all SDGs.

New and improved tools are needed for all six Transformations. They must: help model structural changes over a time horizon of 10–30 years, including financial and economic cost estimates; integrate science, engineering and policy analysis; identify and quantify trade-offs; and communicate strategies and investment trajectories clearly to the public and business sectors. Major efforts are needed to vet and improve the available tools and databases, which should be open-access and made freely available using Creative Commons licenses. They must also be integrated with economy-wide assessments of SDG investment needs and financing strategies, as recently published by the International Monetary Fund[60].

Time-bound benchmarks. To make the Transformations tangible and operational for businesses, governments and other stakeholders, their complexity needs to be broken down into time-bound benchmarks derived from the pathways. Under the Millennium Development Goals, the health sector adopted such time-bound benchmarks, such as the 2003 objective to provide antiretroviral therapy to three million people in developing countries by 2005, which became an organized effort of the World Health Organization to promote rapid implementation. Benchmarks have been developed in the energy sector[30,75], such as phasing out the internal combustion engine by 2030–2035, and decarbonizing the power sector by 2050. Such benchmarks should be derived from integrated pathways, and should offer clarity for the corporate sector and governments on how to implement the six Transformations[75]. They are also critical for defining technology missions[76]. The recently launched Science-Based Targets Partnership (https://sciencebasedtargets.org/) and other efforts require support from the scientific community to fill these gaps.

Stakeholder engagement and co-design. Transformations cannot be designed and imposed from the top down. Broad public support and buy-in are needed for each Transformation, and their implementation must draw on a broad range of communities and sectors[32,62]. In the health sector, the Global Fund to Fight AIDS, Tuberculosis and Malaria has become a key driver of stakeholder engagement and learning[77]. Yet, we lack clear models for organizing these discussions and consultation processes in other areas, and successful models will differ between countries, as they must be mindful of history, customs and government capacity. The scientific community should take on the challenge of developing tools and methods for multi-stakeholder engagement and co-design that help identify perceived trade-offs, ensure technical feasibility of long-term pathways and explain the urgency to act.

Policy tracking, monitoring and evaluation. Finally, the SDGs call for a major effort to mobilize data and monitoring frameworks

to track the Transformations and share lessons on best practice. Outcome data on the SDGs remain incomplete[78]. Filling these gaps will require the integration of official and unofficial data, including those from remote sensing and big data, using mechanisms such as the Group on Earth Observations (https://www.earthobservations.org/) or the Global Partnership for Sustainable Development Data (http://www.data4sdgs.org/). These and other efforts need to be scaled up with support from the scientific community.

A far wider data and knowledge gap exists in the tracking of policies and inputs into the SDG Transformations. The Climate Action Tracker (https://climateactiontracker.org/) has done ground-breaking work in assessing the presence and adequacy of national greenhouse-gas-emission reduction targets with the Paris Agreement, inventorying national policy instruments (policies, regulation, budgets and so on) for energy decarbonization, and determining their adequacy for meeting national targets (Transformation 3). In this way, the Climate Action Tracker has greatly enhanced our collective understanding of whether countries are on track for the Paris commitments and of the policies and investments needed to achieve this. We consider it an invaluable tool for international climate policy, but it covers only G20 members and a few other countries at present. To our knowledge, no such efforts exist for the other five Transformations, where the monitoring of progress draws only on outcome data. This, we believe, is one of the most urgent deficits facing the international scientific community in the next few years.

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J.D.S. provided the initial idea for this paper. G.S.-T. coordinated the writing and prepared the Supplementary Information. All authors contributed to every phase of the study.

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The authors declare no competing interests.

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