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Perspective

Defining a sustainable development target space for 2030 and 2050

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SUMMARY

With the establishment of the sustainable development goals (SDGs), countries worldwide agreed to a prosperous, socially inclusive, and environmentally sustainable future for all. This ambition, however, exposes a critical gap in science-based insights, namely on how to achieve the 17 SDGs simultaneously. Quantitative goal-seeking scenario studies could help explore the needed systems' transformations. This requires a clear definition of the "target space." The 169 targets and 232 indicators used for monitoring SDG implementation cannot be used for this; they are too many, too broad, unstructured, and sometimes not formulated quantitatively. Here, we propose a streamlined set of science-based indicators and associated target values that are quantifiable and actionable to make scenario analysis meaningful, relevant, and simple enough to be transparent and communicable. The 36 targets are based on the SDGs, existing multilateral agreements, literature, and expert assessment. They include 2050 as a longer-term reference point. This target space can guide researchers in developing new sustainable development pathways.

INTRODUCTION

The 2030 Agenda for Sustainable Development,[1] adopted in 2015 by the UN General Assembly, sets an ambitious agenda for the universal pursuit of economic, social, environmental, and institutional objectives, concretized in 17 sustainable development goals (SDGs) and 169 associated targets. Together with other international agreements (such as the Paris Climate Agreement and the Aichi biodiversity targets[2,3]), the 2030 Agenda aims to ensure that development patterns lead to wellbeing and social inclusion while maintaining the Earth's biophysical life support stability systems. Achieving the SDGs will require a fundamental transformation of today's societies.[4–7] Still, it is not easy to understand exactly what is needed. Although for some goals (e.g., climate action, SDG13), literature exists showing how to achieve them, such literature is sparse or lacking for many others. More importantly, hardly any information exists on what is needed for achieving all SDGs together,[5] accounting for the linkages between SDGs and possible synergies or trade-offs.[4,8–12] For example, one way to pursue food security for all (SDG2) would be by increasing production, possibly through more intensive agriculture, which could lead to more fertilizer use and thus emissions of nitrous oxide (SDG13) or leading to water shortages (SDG6). Similarly, using bioenergy to reduce greenhouse gas emissions (SDG13) could lead to an expansion of agricultural land, possibly reducing biodiversity. However, many synergies also exist; e.g., reducing greenhouse gas emissions through expansion of renewable energy (SDG13) also reduces air pollutants emissions, thus improving health (SDG3). Recent studies have looked at achieving multiple SDGs at the national level[13,14] or specific groups of SDGs.[6,15–17] Still, with only a few exceptions, no studies have looked at scenarios to achieve all 17 SDGs simultaneously or the longer-term implications, which is critical for genuinely sustainable planning (noteworthy exceptions include the work of Randers et al.[18] and Soergel et al.[19]). This knowledge gap is also emphasized by various

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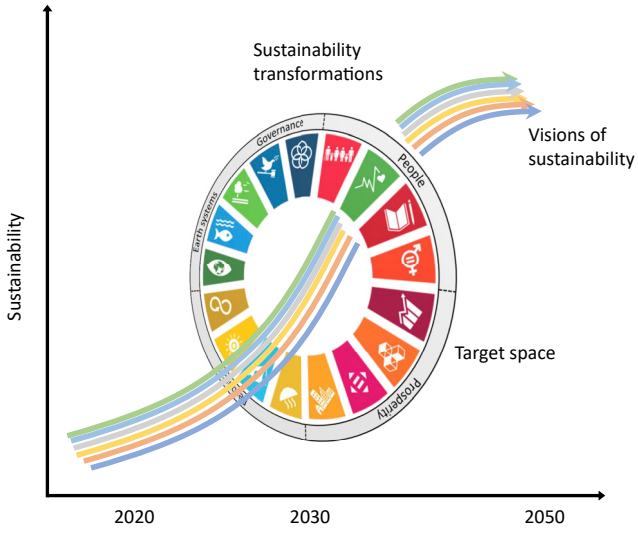

Figure 1. Conceptualization of the target space, showing how it relates to the required societal transformations and the long-term sustainability vision

policy reports and science programs such as the Science-based Targets Initiative[20] and the UN Global Sustainable Development Report.[21] The current situation caused by the COVID-19 pandemic and the recovery process, which could enable or impede pathways toward implementing the SDG, has made this even more important.[22,23] Scenarios showing how SDGs can be met could play a similar role as emission and climate scenarios have in the climate realm; i.e., spur scientific research and help policymakers translate ambitions into concrete action. Identifying pathways to implement the SDGs has become even more urgent due to the slow implementation record.

Any exercise aiming to provide a quantitative analysis of pathways toward meeting the SDGs would need a precise formulation of the target space[24–27]; i.e., a limited set of targets formulated unambiguously and providing comprehensive coverage of the ambition of the SDGs. Although the current 169 targets and 232 indicators allow tracking global and country-level progress on implementing the 2030 Agenda,[28] they are too broad, unstructured, and complex to support quantitative analyses of transformation trajectories and are not always science based. As a result, progress on scenario development at all scales (global, national, or local level) is slowed down by the lack of a relatively simple framework that includes all relevant, sustainable development dimensions. However, defining a target space is not easy. For instance, in several science areas relevant to the SDGs, quantitative projections are not common practice.[29,30] Moreover, any selection of targets automatically leaves out important topics.

Formulating a standardized target space could help the scientific community in analyzing pathways toward meeting the SDGs. A key reason for a standardized set is that no single model will be able to address all aspects of the target space meaningfully. As such, the community should work together with sets of (coupled) models to provide a more comprehensive analysis.[31] The target space and the transformation narratives can be critical for improving comparability and consistency across a broad set of quantitative studies on the SDGs (at the same time, it is also important to propose new indicators and targets than those proposed here to keep heterogeneity, stimulate innovation, and do justice to uncertainty[32]).

This paper proposes such a systematic set target space formulation that can be used for sustainable development scenarios and that can be tested and evaluated in scenario studies. The targets could be used to move beyond the more topic-oriented scenario exercises done so far, such as climate (Intergovernmental Panel on Climate Change [IPCC]), biodiversity (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [IPBES]), and food (Food and Agriculture Organization [FAO]), toward integrated analyses of the people-planet framework. In the paper and the supplemental information (Note S1), we explain why the targets were chosen. Future studies could contribute to this exercise by using it, engaging in further refinement of indicators or target values, and contributing to improved modeling of individual indicators or linkages. As such, the set can be tested in applications (see, for instance, Soergel et al.[33] for a first example) at the global, regional, national, and subnational level, providing insight into the usefulness and applicability of the set. In the paper, we briefly illustrate the use of this set of targets by applying it to available information for a middle-of-the-road scenario.[34] With increasing experience and scenario applications, the target space is expected to be adapted and improved.

DEFINING A SUSTAINABLE DEVELOPMENT TARGET SPACE

The formulation of the target space draws upon expert discussions as part of The World in 2050 (TWI2050) initiative; further information on this initiative and participating institutions can be found at www.twi2050.org. TWI2050 convenes scientists involved in scenario modeling, social and natural scientists, and policy analysts from around the world for collaboration and deliberative consultation for the development and use of sustainable development pathways[5] (Figure 1). TWI2050 has identified six fundamental transformations, describing a set of interventions for simultaneously achieving the SDGs and extending sustainable development beyond 2030: (1) advancing human capacities and demography, (2) establishing responsible consumption and production patterns, (3) achieving decarbonization and inclusive and sustainable energy systems, (4) establishing sustainable land use management and access to food while safeguarding biodiversity of terrestrial and aquatic ecosystems, (5) developing sustainable cities and communities, and (6) aligning the digital revolution with the SDGs[5] (Sachs et al.[7] provided a slightly adapted variant). These transformations were kept in mind in selecting the target space indicators (see Note S2 for the connections). Around 60 scientists involved in TWI2050 assisted in formulating the target space. This involved the selection of indicators, as well as the associated target values. There were several steps in the process (Figure 2): (1) formulation of key principles for the target space and selection criteria; (2) the review of existing sets of indicators and targets in the literature, international agreements, and associated with the SDGs; and (3) the final selection of a set of indicators and targets.

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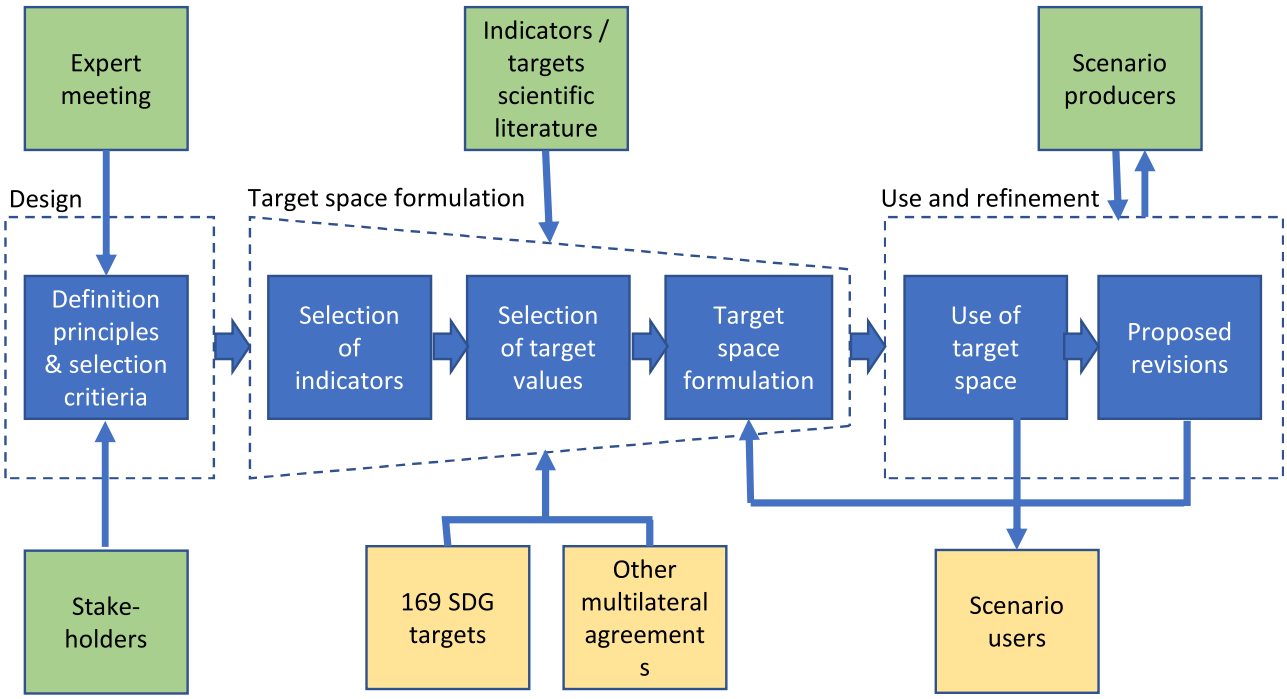

Figure 2. The process for defining and applying the target space

Principles and criteria for indicator selection

First, a list of principles for selecting indicators and setting targets was developed (Table 1). A first principle is to ensure that the indicators are relevant for society; i.e., they link to the societal agenda as expressed in the SDGs, which are the outcome of a global political consultation process. The set also needs to be science based; i.e., it should be consistent with the insights of global sustainability science. This leads to the third principle that a longer-term perspective must be included (valid for 2030 and beyond). The fourth principle emphasizes that indicators need to be robustly quantifiable to enable quantitative analysis. The fifth principle of operational simplicity, transparency, and usability aims to ensure the relevance of the quantitative analysis for policymakers (Table 1). This, for instance, means that the number of targets needs to be limited. A sixth principle is that targets need to be actionable (i.e., sensitivity to human decision making) and (at least theoretically) achievability. Finally, comparable data and knowledge also need to be available. A key argument for the relevance beyond 2030 is that the transformation toward sustainable development is a long-term process and that therefore it is essential to check whether developments are also in line with these long-term goals (e.g., for climate change, a significant emission reduction in 2030 is only a step toward achieving net-zero emissions mid-century; see also Moallemi et al.[35]). The fact that short-term targets are not always met provides another reason for also adding a long-term focus.

Our ambition to keep the sustainable development target space analytically tractable and transparent subsequently translated into a criterion to choose only two to three targets per SDG. One way to do so was (if relevant) prioritizing those targets that represent endpoints in terms of the actual desired state and not the means of achieving this state. Another way is to avoid overlap between target indicators. As the SDGs are interlinked, an indicator selected for a given SDG can also cover aspects of other SDGs (for example, access to the internet and financial institutions relates to SDG9 on innovation and covers aspects of SDG10 on reducing inequality). Each target should also be suitable for quantitative analysis and sensitive to policy choices. Table 1 discusses in more detail how the key principles were applied in indicator selection and setting targets.

Selection of targets and target values

Based on the above criteria, the expert deliberations proposed a set of targets[37] that has been iteratively refined based on the above criteria and existing literature (Table 2). Given the first principle, we started with an initial list of targets as part of the 2030 Agenda and multilateral agreements, complemented with the (scientific) literature, for instance, the Planetary Boundary indicators[27,36,38] (more specific references are provided in the paragraphs describing indicator choice). Regarding the choice of the specific numerical target values, the criteria set in Table 1 implied that values are (1) preferably, directly taken from the 2030 Agenda and other international agreements or (2) directly taken from the scientific literature. As an alternative, (3) the values of top-performing countries have been used, or (4) values that are assessed to be directly consistent with the basic principles underlying the SDGs (e.g., zero hunger). The Sustainable Development Solutions Network (SDNS) network applied a somewhat similar method for their domestic targets.[39] In some cases, the targets needed to be defined more precisely to allow quantitative evaluation (e.g., the notion of hunger needs a specification of a number of kilocalories per person per day). Finally, our final set also includes examples for

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Table 1. Criteria for defining the sustainable development target space

Key principles underlying the target space: Target indicators should be	Derived criteria for selection of targets	Derived criteria for target values
Societal relevance	the target space addresses areas of sustainable development organized around the 17 SDGs; wherever possible, indicators and target values directly related to the SDGs or objectives from other international agreements are used	
Science-based	the indicators need to address the most pressing dimensions of human development (people), socio-economic wellbeing (prosperity), national and international security (peace), and global environmental change (planet) as discussed in the scientific literature, such as the processes prioritized in the Planetary Boundaries framework[36]	where consensus exists on science-based targets that must be achieved by 2030 or later, these should be used
Valid for 2030 and beyond	the indicators should relate to both the SDG time frame (2030) and the long-term (2050 and beyond) and account for path-dependency	for 2050, target values either retain absolute 2030 measures (e.g., zero hunger, energy access for all) or even improve upon these values; in the latter cases, the values are set to achieve a decent life for all
Quantifiable	the targets should be well suited for inclusion in quantitative analyses, capturing as many features as possible in state-of-the-art integrative models; they also need to be unambiguous and measurable	target values need to be specified clearly and with appropriate precision in order to be suitable for quantitative analysis
Transparent	the set should be clearly defined, and individual indicators should be easy to understand (e.g., avoiding multi-dimensional indices); the number of indicators per issue should be as low and complementary as possible while capturing the global features of Agenda 2030; we, therefore, aim to have at most two or three indicators per SDG, and some indicators assigned can be relevant for multiple SDGs; we prioritize selecting indicators that describe end values of system transformation rather than the means to achieve them	target values should ensure consistency across the indicators for the different SDGs and be linked to the principles underlying the SDGs and the objectives of other international agreements
Actionable and achievable	the indicators should be actionable and sensitive to policy initiatives (and thus link to system transformations)	the target values are derived from existing agreements; targets should be reachable, for instance, demonstrated by some countries reaching the target
Availability of data and knowledge	indicators are only useful if data are available to monitor progress	the target values need to be rooted in data and knowledge

which target values could not yet be provided, such as quantifying peace by measuring the reduction of conflict-related deaths until 2030 and 2050. Two challenges have to be kept in mind when applying the target space. First, the targets are interlinked.[10,11] Synergies between SDGs reinforce the achievement of different targets (e.g., access to drinking water improves health), whereas trade-offs may limit or hinder the achievement of other goals.[5,7] Second, although several targets are universal and can be applied at different geographic scales, others are currently focused on the global scale. We assume that, in quantitative analysis, model teams will find ways to deal with these challenges and encourage the international community to explore further elaboration in future applications of the proposed target space.[40]

THE SELECTED INDICATORS AND TARGET VALUES

We discuss the target and indicator selection in five clusters and provide additional information on the choices in the supplemental information (Note S1). The clusters are based on the key elements of sustainable development introduced in the preamble of the 2030 Agenda[1]; i.e., (1) mobilizing people's potentials in dignity and equality, above all requiring the end of poverty (people); (2) ensuring that all human beings can enjoy prosperous and fulfilling lives (prosperity); (3) protecting the planet from degradation, including ensuring more sustainable management of key resources (planet); and (4) ensuring the development of well-governed, peaceful, just and inclusive societies that are free from fear and violence (peace). We have split the planet element into

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Table 2. Targets and indicators for the 2030 and 2050 target space

SDG	Normative goal	Indicator	Current situation (around 2015)	2030 target	2050 target
(1) No poverty	end extreme poverty	number of people below international poverty line	889 million (13%)[41]	0	0
(2) Zero hunger	end hunger	number of people undernourished (below MDER)	795 million (11%) people undernourished[42]	0	0
	healthy diets for all	number of people with obesity (BMI >30)[43]	636 (9%) million in 2010[44]	0	0
(3) Good health and wellbeing	achieve adequate health care for all	healthy life expectancy at birth (years)	global mean 63.12 years country range [45.6–75.2][45]	>65[27]	>70
		under 5 mortality rate (deaths per 1,000 live births)	global mean 43; 99 in sub-Saharan Africa[46]	25	12
(4) Quality education	universal lower secondary education	share of leaving cohort completing lower secondary education	90% primary and 76.7% lower secondary completion rate[41]	80% secondary; 100% primary	100% secondary
(5) Gender equality	end gender discrimination in education	the gender gap in mean years of schooling of population aged ≥15 years	global mean: 0.79[47]	0	0
	achieve gender pay parity	female estimated earned income over male	52%–87%[48]	1	1
(6) Clean water and sanitation	universal access to clean water	population without access to improved water source piped	660 million (9%)[41]	0	0
	universal access to sanitation	population without access to improved sanitation facility	2.4 billion (32%)[41]	0	0
	end water scarcity	the area under water stress (water stress index for most water-scarce month/ season)	11%[49]	no increase	no increase
(7) Affordable and clean energy	universal modern energy services for all	population cooking with traditional biomass	2.8 billion (37%)[50]	0	0
		population without basic electricity access	1.1 billion (13%)[50]	0	0
(8) Decent work and economic growth	work for all	unemployment rate (formal economy)	6%[42]	6%[27]	6%
	global economic convergence	the ratio of GDP *per capita* of a country to the average OECD GDP *per capita* (both in PPP)[41]	average low-income countries: 5.0%; average lower-middle-income countries: 16.7% (both 2018)	low-income countries: 2-fold increase; lower-middle income countries: increase by 50%	low-income countries: 4-fold increase (reaching at least 15%); lower-middle-income countries: 3-fold increase

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Table 2. *Continued*

SDG	Normative goal	Indicator	Current situation (around 2015)	2030 target	2050 target
(9) Industry, innovation and infrastructure	R&D	R&D intensity, i.e., private and government-financed gross domestic R&D expenditure (GERD) in per cent GDP	1.7%[51]	3%[52]	3%
	Universal access to ICT	the proportion of the population using the internet (%)	46%[53]	95%	95%
	universal access to finance	the proportion of the adult population with an account at a financial institution (%)[54]	69%	middle- and high-income countries: 90% low-income countries: 80%	95%
	fast access to an economic hub	travel time to the nearest city with at least 50,000 inhabitants[55]	high-income countries: less than 1 h for 90% of the population low-income countries: 20% have to travel for more than 3 h	middle- and high-income countries: less than 1 h for 90% of the population low-income countries: less than 3 h for 90% of the population	all countries: less than 1 h for 90% of the population
(10) Reduced inequalities	decrease relative poverty	number of people below 50% of median national daily income (% of the population)[56]	>1.4 billion (~20%) people	15%	10%
(11) Sustainable cities and communities	decent housing for all	population living in slums (urban)	880 million (30% of urban population)[42]	10%	0
	improve air quality in cities	population exposed to annual average PM2.5 > 25 μg/m^3[57]	65%[41]	20%	10%
(12) Responsible consumption and production	reduce waste and pollution	food loss and waste	33%[58]	<15%	<15%
		municipal material recovery	34% in OECD[59]	59% (top 5 countries 2015)	–
(13) Climate action	limit global warming	well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels	55 $GtCO_2$-eq[34]	pathway toward long-term goal; or globally at least below <27–40 GtCO2-eq[60] (1.5 and below 2°C, 50th percentile)	pathway toward long-term goal; or globally at least below <7–18 GtCO2-eq[60] (1.5 and below 2°C, 50th percentile)
(14) Life below water	balance phosphorus in oceans	P flow from freshwater systems into the ocean	~22 Tg P y–1[36]	11 Tg P y-1[36]	11 Tg P y-1[36]
	sustainably manage marine resources	the proportion of fish stocks within biologically sustainable levels[61]	65%[61]	90%[62]	100%[62]

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Table 2. *Continued*

SDG	Normative goal	Indicator	Current situation (around 2015)	2030 target	2050 target
(15) Life on land	halt land-system change (deforestation)	global: area of forested land as % of original forest cover biome: area of forested land as % of potential forest	~4,000 ha[63]	no further loss of primary forest	global: 75% (75%–54%), specified by forest type[36]
	balance nitrogen in soils	industrial and intentional biological fixation of N	~150 Tg N y^{-1}[36]	62 Tg N y^{-1}[36]	62 Tg N y^{-1}[36]
	protect biodiversity	BII		no degradation from 2020 onward	no degradation from 2020 onward
(16) Peace, justice, and strong institutions	reduce violence and related deaths	battle-related deaths and fatalities from one-sided violence	>93,000[64]	0 per country/year[b]	0 per country/year[b]
	promote the rule of law and ensure equal access to justice for all	equality before the law and individual liberty index[a]	global: 0.69 (based on Coppedge et al.[65])	increase all individual country scores, at least >0.9[b]	increase all individual country scores, at least >0.9[b]
	ensure responsive, inclusive, participatory, and representative decision making	equal access index[a]	global: 0.63 (based on Coppedge et al.[65])	increase all individual country scores, at least >0.9[b]	increase all individual country scores, at least >0.9[b]
(17) Partnerships for the goals	increase statistical capacities	statistical capacity score: source data (second dimension of the Statistical Capacity Indicator by the World Bank)	62.0 (global average for 149 countries)[66]	increase up to 100 for all countries	increase up to 100 for all countries
	strengthen domestic resource mobilization	total government revenue	global average: 24%–28% (w/o natural resources) for 2011–2015 (based on ICTD/UNU-WIDER[67])	increase to 20% for countries currently below this threshold, otherwise, maintain	maintain the level of 2030 the threshold without the revenue generated by the exploitation of natural resources
	enhance interconnection with global civil society	number of international NGOs of which a country is a member, whether directly or through the presence of members in that country[a]	Global average 386 (based on UIA,[68] countries <500,000 excluded)	increase value above the 25th percentile based on data of 2017 for countries below this threshold, otherwise maintain	increase value above the 25th percentile based on data of 2030 for countries below this threshold, otherwise maintain

Most targets can be applied at the regional or national level. MDER, minimum dietary energy requirement; BMI: body mass index; PPP, purchasing power parity; ICT, information and communication technology; PM2.5, fine particulate matter smaler than 2.5 micron: P = phosphorous; N = nitrogen; BII, biodiversity intactness index; NGOs, non-governmental organizations.
[a]Indicators for which we are unaware of model-based thresholds.
[b]Indicators where we are unaware of model-based long-term projections.

two clusters on planetary integrity and sustainable resource management. The first set focuses on the functioning of the Earth system itself; the second on the interface between the human and Earth system: the use of key resources, including land, energy, and water. The resulting clustering of targets and indicators serves as an accessible yet meaningful form of presenting the high number of indicators in a readable way. These clusters and the sequence of our discussion do not imply any form of hierarchy and do not consider interactions between SDGs yet. Using the indicators in model-based scenario analyses will do so (and could be combined with the six transformations[5,7]). Table 2 summarizes the target space organized by SDG. More information about alternative indicators and why we opted for our selection can be found in the supplemental information (Note S1).

People (SDGs 1, 3, 4, and 5)

The SDGs addressing poverty eradication, health, education, and gender equality together represent a concept of human

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development. Several indices have previously been used to capture the multi-dimensional nature of human development, aiming to assess progress over time beyond economic growth. A widely used indicator is the United Nations Development Programme (UNDP) Human Development Index (HDI), which encapsulates three dimensions of development: leading a long and healthy life, acquiring knowledge, and achieving a decent standard of living.[69] In selecting indicators, we build on this by including the number of people suffering from extreme poverty for SDG1, the healthy life expectancy and under-five mortality rate for SDG3, the completion of secondary education for SDG4, and gender gaps in education and income for SDG5.

For SDG1, it is clear that one indicator needs to be related to the objective of no one living in extreme poverty by 2030 as a basic requirement. A key question is how to define extreme poverty. The World Bank global poverty line[70] is chosen as the threshold for 2030 as it is well established and researched. The global poverty line has been periodically updated to reflect increasing costs of living across the world. Where Target 1.1 specifically mentions $1.25 per day, the World Bank has updated the absolute poverty line to $1.90 per day (US$ 2011). We use US$2 (US$ 2015) *per capita* per day for 2030 and 2050 for practical reasons and kept it constant over the time period (given the correction for inflation). Relative poverty is also included under SDG10 and discussed in the Prosperity cluster. SDG3 aims at ensuring healthy lives. Healthy life expectancy at birth is often proposed as a summary indicator.[27] The set of SDG targets includes several other indicators, including maternal mortality rates, and many other indicators are also used in the literature. However, the advantage of the healthy life expectancy indicator is that it is all-encompassing. It provides an opportunity to reduce the number of indicators as envisaged by our selection criteria. The SDG target on under-five mortality rate is used to track progress in developing countries. The SDG target level of 25 deaths per 1,000 live births is taken for 2030, further halved by 2050 to increase progress. Although this is still far from levels currently recorded in developed countries, it is still ambitious and achievable. Alternative indicators that were considered include normal life expectancy at birth, a goal of avoiding 40% of premature deaths,[71] and the median health-related SDG index used by the Global Burden of Disease study.[45] Although the latter is also an encompassing indicator, it at the moment requires a too-comprehensive set of underlying indicators to be modeled. SDG4 aims for quality education. The addition of universal secondary education expanded the millennium development goals (MDGs) ambition, which targeted universal primary education only. This addition is based partly on insights that, for poor countries to escape from poverty, universal primary education is not enough and therefore needs to be complemented by secondary education for broad segments of the population.[72] We chose the share of young people achieving lower secondary education as this covers the compulsory schooling time in most countries and reliable data are available. Considering current enrollment rates in primary education, achieving 100% completion of lower secondary education by 2030 is practically impossible, so the target values proposed are 80% in 2030 and 100% in 2050 following medium education and population projections.[69] Alternative indicators may include literacy rates, expected years of schooling, participation in early childhood education, the share of the total population with lower secondary education, a measure of the quality of education through graduate employment, and mean years of schooling. SDG5 aims for gender equality. Out of the broad domains covered by this SDG, we chose education and income to track female empowerment. The target values aim at full equality in 2030, as called for by SDG5. Although some models cover differences in education, the wage gap is currently addressed in very few models and might be a future alternative indicator. The advantage of the education-gap indicator is that it is directly related to future capacity and has an established science-based link with other indicators such as fertility levels. Other indicators that are used to track current progress regarding gender equality include the female-to-male labor force participation rate, proportion of women in national parliaments, share of women in management roles, legal gender discrimination, and rates of sexual violence. However, none of these are currently captured by integrated assessment models, and data quality varies.

Prosperity (SDGs 8, 9, 10, and 11)

SDGs 8, 9, 10, and 11 are closely linked in their focus on socio-economic conditions and, as a cluster, envisage societies and economies that offer a prosperous and fulfilling life for all. SDG8 aims for sustained and inclusive economic growth and full and decent employment. As prosperity in high-income countries is no longer driven by economic growth per se,[73] a focus is placed on sufficient economic growth in low- and lower-middle-income countries, eventually leading to a convergence of living standards. We, therefore, propose an indicator of economic convergence as measured by the ratio of gross domestic product (GDP)/capita in the target country to the average Organization for Economic Co-operation and Development (OECD) GDP/capita (both measured in purchasing power parity, ppp). Our quantitative targets are based on historical examples of rapid GDP/capita growth and income convergence, particularly the Asian tiger economies in the 1960–1995 period and China post 1990. In these cases, GDP/capita relative to the developed economies multiplied by a factor of ≥ 4 in a few decades, with *per capita* growth rates of $\sim$7%.[74] As an aside, we note that these targets will be met for many countries under the GDP and population quantification of the Shared Socio-economic Pathways (SSP1) scenario, a set of community scenarios mostly used in climate research.[75] The second proposed indicator for SDG8 is related to employment and decent work (targets 8.5–8.8). Work serves two crucial purposes. It gives individuals access to financial income for entertaining a life of their choosing, and it provides meaning and organizing structure to life. Because a decent income for all is implied by the SDG10 target constraining relative poverty (see below), we focus here on sufficient availability of decent employment opportunities and choose the unemployment rate as indicator for the functioning of labor markets. However, we acknowledge that labor participation rates are also relevant indicators as higher participation can generate both social and economic value,[76] and that the future of work will likely change substantially with increasing digitalization and automation.[77] We, therefore, may eventually require a broader notion of activities with economic or societal value to cover the goal of decent work. Following O'Neill et al.,[27] we set a target of less than 6% of the labor force being unemployed

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(or, more broadly, being without valued activity). SDG8 also contains the fundamental goals of eradicating forced and child labor (target 8.7), protecting labor rights, and promoting a safe working environment (target 8.8). These fundamental goals are not singled out explicitly in our set of indicators. However, they are implied by a range of indicators relating to poverty eradication (SDG1), universal education (SDG4), broad access to socio-economic activities (SDG9), decent income (SDG10) and living conditions (SDGs 3, 6, 7, 11), and gender equality (SDG5).

The indicators proposed for SDG9 aim to capture multiple aspects of infrastructure (both physical and non-physical) and innovation, focusing on technologies and services that can serve as critical enablers. Following existing policy targets for investing into innovation, we select a country's research and development (R&D) intensity, including both private and government R&D expenditures, as a proxy for innovation. With regard to infrastructure, we select three complementary indicators broadly covering access to physical and digital markets, information, and finance: the fractions of the population with access to the internet, access to financial services, and access to economic hubs represented by travel time to the nearest major city[55] as proxies for infrastructure. SDG10 calls for reducing inequality both across and within countries. The inequality dimension across countries is already covered by the income convergence indicator proposed for SDG8. For inequality within countries, we focus on relative poverty and use the OECD definition[56] of people living below half of the national median income (cf. target 10.2.1). To derive a quantitative target for this indicator, we examine national statistics for the Gini index taken from the World Development Indicators.[41] In recent years, the lowest measured Gini indices are around 25, with around 15%–20% of the countries with available data having Gini indices below 30. We, therefore, take a value of $\leq$30 as an ambitious but still realistic target to be reached by 2050. Under the assumption of a log-normal income distribution, we can analytically relate the Gini coefficient to our proposed indicator. This yields a target of at most 10% of the population living below half of the median income (independently of the average income level) in 2050. We propose an intermediate target of at most 15% of the population in relative poverty by 2030. Finally, for SDG11, we focus on two central aspects of sustainable cities: adequate and safe housing, represented by the number of people living in slums, and a healthy environment represented by the share of people exposed to an annual average pollution level of particulate matter with a diameter of 2.5 μm or less (PM2.5). The threshold for PM2.5 follows the upper value (24-h mean) of the World Health Organization (WHO) guideline[57] (WHO, 2018) and coincides with the annual average threshold value used by the European Union (EU). As targets, we propose that less than 10% of the urban population is exposed to higher annual average levels of PM2.5 by 2050 and less than 20% by 2030. These values are comparable with current values in the EU.[78] Taken together, the selected indicators provide a robust proxy for the ability of an economy to deliver equal access to decent work, income, and living conditions.[73]

Planet integrity (SDGs 13, 14, and 15)

The SDGs on climate action and aquatic and terrestrial biodiversity relate to the condition of the natural environment and the planetary boundaries.[36,79] Given the successful application of the Planetary Boundary framework in many studies, we have decided to look for synergy for some indicators and goals. For SDG13, we follow the target of the Paris Agreement, i.e., well below 2°C, and pursue efforts to stay below 1.5°C. Global integrated assessment models (IAMs) can use this target directly. However, other models (e.g., at the national scale) need derived information, such as existing IAM emission profiles[60] or national carbon budgets over a specific period. We have selected a greenhouse gas emission target but did not specify the downscaling method given the political choices involved (which might relate to the national context). Moreover, we also left it up to the user to interpret the Paris Agreement for the temperature goals and only set an upper bound. Future work could further specify this target. One aspect of SDG14, ocean acidification, is also related to CO_2 emissions and is therefore assumed to be covered by the climate target. In addition, for SDG14, eutrophication can be covered by the phosphorous flow from freshwater systems into the ocean (based on the planetary boundaries) or the index of coastal eutrophication (selected from the SDGs).[80] The latter is more refined but does need further modeling of coastal systems. Further, the fraction of fish stocks within safe biological limits[61] represents the sustainable use of fish resources.[36] We also considered the Ocean Health index, or other work on biodiversity indicators for aquatic systems (such as the mean species abundance), but considered the work not advanced enough to add them at this stage, given the relatively complicated calculation schemes. For terrestrial biodiversity, in principle, multiple dimensions of biodiversity would need to be covered.[81] In order to limit the number of targets, however, the Planetary Boundary indicators are proposed; i.e., the minimum extent of forest cover in different forest biomes, the balance of nitrogen into soils, and the biodiversity intactness index (BII).[82] For the latter, alternative aggregated biodiversity indicators also exist (e.g., the number of species). A comparison project can possibly show whether these can be used as a replacement (if applied relative to reference year).

Sustainable resource management (SDGs 2, 6, 7, and 12)

The consumption and production of food, energy, and water (nexus resources) play a crucial role in many sustainable development challenges, while large parts of society still lack sufficient access.[83–85] The relevant SDGs aim to ensure access to these critical resources for all people while also limiting possible negative consequences of their production and use.

The first indicator is the number of undernourished people (proposed by many other publications, including O'Neill et al.[27]). The target of 0 people undernourished by 2030 is taken from the SDG and needs to be sustained beyond 2050. As the threshold for undernourishment, we apply the minimum daily energy requirement (MDER, kcal/capita/day) suggested by FAO (2017). FAO (2017) calculates country-specific MDERs. The 2030 and 2050 global average minimum thresholds are based on calculations by Hasegawa et al. for SSP1.[86] The future mean MDER is calculated for each year and country using the mean MDER in the base year at the country level[25] and allowing for an adjustment coefficient for the MDER in different age and sex groups.[26] This can be done using future population

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demographics[27] to reflect differences in the MDER across age and sex.[86] As SDG2 also covers malnourishment, the prevalence of malnourishment and stunting and wasting could also have been considered as alternative indicators, but the proposed indicator is assumed to be more encompassing. In the future, it might be interesting to include an indicator going beyond the mere energy content of diets (kcal) and include aspects related to health.[87,88] We also added an indicator related to obesity. Obesity is on the rise globally, also in developed countries, and has severe health impacts (linked to SDG3), but also clear links to consumption patterns (SDG12) and the overall impact of the agriculture system on the environment (also given the role of animal products). Work on diets in relation to sustainable development (e.g., EAT-Lancet Commission) and as well as health impacts (non-communicable diseases) is evolving,[89] but setting target values and related thresholds still poses a challenge as it is closely connected with lifestyle. SDG2 also covers agriculture and food production. We considered an indicator focusing on sustainable agriculture, but it should also be noted that it also links to the nutrient, energy, water, and climate indicators proposed under the environmental and resource SDGs (6, 7, 13, 14, and 15). For that reason, no additional indicator was added here.

SDG6 covers water demand by human beings and the environment. The first indicators look at access to clean water. We use a threshold of sufficient access of 50L/per/capita/day recommended as a basic water requirement.[90] This is proposed as a universal threshold focusing on meeting basic needs, including water for drinking, basic sanitation, plus some water for cooking and bathing. The second indicator is access to sanitation services. Finally, for water scarcity, we use the proportion of an area or region under water stress. Here, water stress is defined as the ratio between total water use and availability. A value above 40% is defined as areas suffering from severe water stress.

SDG7 calls for both access to energy for all and the sustainable use of energy. We propose to focus on energy service levels (final energy demand), including heating/cooling and mobility service per household per day that allow a decent life (see Grubler et al.[91]), going beyond mere access. What is deemed decent is subject to national circumstances (e.g., also related to climate zone). Because of advances in technology and living standards, energy requirements in 2050 are subject to change.

For SDG12, a range of indicators can be considered. Our selected indicators—food loss and waste and municipal material recovery—only cover a subset of the relevant resources involved in society's processes of production and consumption, and target values will have to be even more ambitious in the long run. However, they can be regarded as illustrative of the capabilities of society to manage and recycle resource flows. These indicators are also well established—at least in industrialized countries—in statistical reporting and can be captured in a modeling framework in a stylized way (technologies, economic incentives). Suitable alternatives could be more comprehensive indicators and indices such as the human appropriation of natural primary productivity (HANNP),[27] the ecological footprint, the material footprint, the global food loss index, or recycling rates, but these indicators are hardly covered by models yet. Further development could also focus more on circular economy indicators and overall efficiency.

Peace, institutions, and implementation (SDGs 16 and 17)

Peaceful, just, and inclusive societies and global partnership are not only desired outcomes of the 2030 Agenda but also serve as essential enablers to achieve all other SDGs.[92–94] Indicators to measure peace and political institutions have been used to project the future.[33,95] We use the number of battle-related deaths[64] to gauge progress toward more peaceful societies. We apply the equality before the law and individual liberty index[65] and the equal access index[65] to measure the development of robust and inclusive political institutions (see also Note S4). For SDG17, the inclusiveness of the international civil society (data provided by the Yearbook of International Organizations[96]) can be used to assess viable societal partnerships. As the availability of an adequate set of financial means will also be crucial,[97] we propose to measure the role of governments with the indicator of total revenue as a percentage of GDP,[27,67] excluding revenues earned from natural resources. This last aspect is key to avoiding goal conflict and trade-offs with other SDGs. Finally, we propose the source data dimension of the Statistical Capacity Indicator[98] to capture the availability of crucial data for designing, implementing, and evaluating policies toward the achievement of the SDG.

EXAMPLE APPLICATION BASED ON CURRENT SCENARIOS

In order to show the relevance of the targets, we use the target space to evaluate the projected trends in the so-called SSP2 scenario, the middle-of-the-road pathway from the set of SSPs mentioned before, which describe different trajectories for socio-economic development and consequences for the Earth system.[34] SSP2 represents a scenario describing median trends for population and economic growth, technology, lifestyle, and other variables within the set. Here, we use the SSP2 scenario to illustrate how the target space can be used within the broader range of values across other SSPs (see Note S3 for a brief description of the information used). The SSP2 scenario has been elaborated in multiple studies by different models but using the same storyline and key assumptions. The SSP values are illustrative as they are not based on a single model but have been derived from several publications elaborating on these scenarios.

The results (Table 3 and Figure 3) highlight that the SSP2 scenario depicts some improvements over time for most targets. However, these improvements are insufficient to meet all targets that were set for 2030 or 2050. For many environmental targets, developments continue to go in the wrong direction (i.e., away from the target) even in the scenario among the SSPs that moves most in the direction of sustainable development (SSP1). We conclude that the implementation of sustainability policies needs to be enhanced significantly across the socio-economic and environmental domains to reach the SDGs. The quantitative scenarios literature does not really include Sustainable Development Pathways that manage to meet all SDGs. Hence, the SSPs serve as a useful starting point that can be extended by additional elements to cover the full target space and thus enable a comprehensive assessment of SDG interactions and long-term sustainability.[99] Such scenarios can show the implications of

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Table 3. Example of use of the target space using data published for the SSP scenarios in various studies

				2030		2050		
		Target 2050	2015	SSP2	SSP range	SSP2	SSP range	References
SDG1: # people in absolute poverty	millions	0	886	441$^{(0)}$	286–655	119$^{(0)}$	22–563	Rao et al.[100]
SDG2: # people suffering from hunger	millions	0	837	295$^{(0)}$	188–560	92$^{(0)}$	13–585	Hasegawa et al.[101]
SDG3: <5 mortality	per 1,000	12	43	45$^{(0)}$	31–71	32$^{(0)}$	15–70	Lucas et al.[102]
SDG4: # people w/o secondary education	millions	0	1,687	2,396$^{(-)}$	1,839–3,826	2,108$^{(-)}$	1,607–4,875	Kc and Lutz[103]
SDG5: schooling gender gap	years	0	1	0.5$^{(0)}$	0.5–0.7	0.3$^{(0)}$	0.2—0.6	Kc and Lutz[103]
SDG6: water stress	% area	0	7	7.0$^{(-)}$	7–7.1	8.3$^{(-)}$	7–8	Byers et al.[104]
SDG6: # people w/o sanitation/ clean water	millions	0	4,127	3,636$^{(0)}$	79–4,251	2,199$^{(0)}$	84–3,979	Parkinson et al.[105]
SDG7: # people w/o access to clean cooking	millions	0	2,590	3,240$^{(+)}$	1,232–3,742	2,323$^{(0)}$	574–3,904	Van Vuuren et al.[106]
SDG7: # people w/o access to electricity	millions	0	1,810	845$^{(0)}$	144–1,080	471$^{(0)}$	89–1,015	Van Vuuren et al.[106]
SDG10: # people in relative poverty	millions	0	2,232	2,621$^{(-)}$	2,326–2,909	2,816$^{(-)}$	2,055–3,621	Rao et al.[100]
SDG11: # people with poor air quality	millions	0	4,684	4,825$^{(-)}$	4,683–5,184	4,966$^{(-)}$	4,683–5,685	Rao et al.[107]
SDG13: CO_2 emissions	$GtCO_2/y$	18	42	47$^{(-)}$	42–55	57$^{(-)}$	42–64	Riahi et al.[34]
SDG15: loss of forest cover	Mkm^2	1,500	2,206	2,232$^{(-)}$	2,211–2,332	2,253$^{(-)}$	2,122–2,429	Popp et al.[108]

The symbols show the evaluation of the scenario against the target values: $^{(-)}$, situation becomes worse compared to 2015; $^{(0)}$, situation improves but the target is not met; $^{(+)}$, target is met). The SSP2 scenario currently only provides information for a subset of the indicators of the target space.

achieving all (or a comprehensive set of) SDGs and highlight the synergies and trade-offs associated with specific response strategies, the critical choices, and the (im)possibilities of meeting the SDG goals in 2030 under different assumptions. A first example is provided by Soergel et al.[19]

THE WAY FORWARD

The target space formulation presented above is critically important to provide a consistent analytical framing for quantitative analysis of the required transitions toward sustainable development. It provides an initial framework to guide the analyses of how to achieve the SDGs simultaneously. Using a common, transparent, and science-based definition of the targets permits the scientific community to work together on this endeavor and to start from a set of comparable and internally consistent assumptions. In many ways, the proposed approach for the SDGs is similar to how the climate research community has formulated pathways for meeting the goals of the Paris Agreement, which were subsequently used in the scientific assessments of the IPCC to formulate consistent messages for policymakers. Developing a set of Sustainable Development Pathways requires organizing a comprehensive program for model-based scenario analysis focusing on systems transformations toward the quantitative goals of the target space. This, in turn, requires the pursuit of model improvements to deal better with sustainable development needs.[109] The current formulation of the target space should be understood as the first step of an iterative process among the worldwide scientific community and the policymakers and other stakeholders with interests in these pathways.

One challenge in application represents scale. In principle, the targets selected here should also be applicable at the regional or national scale (instead of the global scale). However, this will sometimes involve specific choices. This is even stronger moving to the subnational scale. Such choices might be related to distributional questions, to the local context (including even the understanding of sustainable development issues) and local capacity and data availability. This becomes even stronger for local communities and small businesses. Moallemi et al.[110] discuss some of these issues in more detail. By itself, scalability is a highly desirable characteristic as it can relate global-scale concerns to action at the national or local scale. To illustrate some of the issues, looking at climate change at the national scale does require allocating the emission budget at the global scale to the national level, related to fairness issues. Similar issues relate to the total phosphorous flow into the ocean. Political discussions on how much an individual country can and will achieve and the question of compensation payments are relevant, as we already see in the climate debate. Another example involves targets like no extreme poverty or hunger, which strongly depend on local contexts. All in all, this means that further attention to the applicability of the target space at local levels and the methods involved is needed.

Other critical issues for further refinement are related to evaluating the indicators and target values, the treatment of non-linearities and interdependences within the target space as it evolves to 2050 and beyond, and the coherent use of indicators at different geographical scales.[40] In several cases, we have not yet formulated concrete targets. In other cases, we indicated that our current initial proposals could be improved, for example, due to limitations of data and modeling capacity. All these improvements will require more interdisciplinary engagement across sustainability science communities. Especially social science communities interested in modeling need to be

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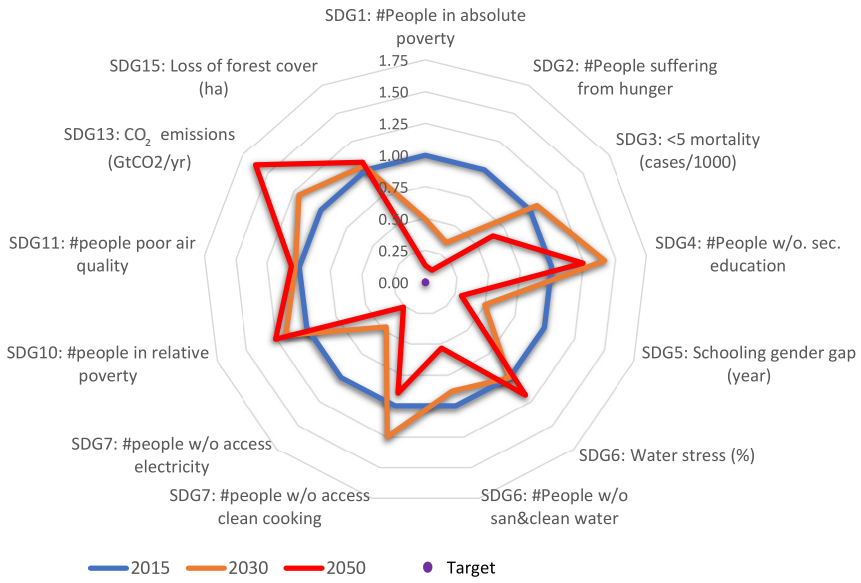

Figure 3. Example of use of the target space, using data published for the SSP2 scenario in various studies

1 = 2015, 0 = target value (values larger than 1 indicate a worsening compared to 2015; in between 0 and 1 indicates an improvement but target is not met).

engaged to advance the target space further. We see the need for an SDG-focused science-policy network, facilitating regular meetings to compare results and exchange experiences with the target space framework. Ultimately, it will thus be up to societal actors, policymakers, and scientists to refine this target space by developing a tractable set of indicators and targets that can be used realistically in integrated policy and impact assessments consistent with the spirit and goals of the original 2030 Agenda.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2022.01.003.

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AUTHOR CONTRIBUTIONS

D.v.V. coordinated the writing of the paper. C.Z. coordinated the data collection for the sample application. All authors contributed to the analysis and the writing of the paper.

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One Earth, Volume *5*

Supplemental information

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Note S1: Supporting information for indicator selection

People (SDGs 1, 3, 4 and 5)

SDG1 (no poverty), SDG3 (good health and well-being), SDG4 (quality education) and SDG5 (gender equality) all form fundamental building blocks for human development. The issue of human development is also directly related to the SDGs in other clusters. Several indices have previously been used to capture the multi-dimensional nature of human development, aiming to assess progress over time beyond economic growth. Most used is the UNDP's Human Development Index (HDI) that encapsulates three dimensions of development, concerned with the abilities to lead a long and healthy life, acquiring knowledge and achieving a decent standard of living[1]. The focus here is on tracking advances towards improving basic aspects of human development. Through complementary indices, such as the gender development index and inequality-adjusted HDI, which both built on the general HDI, UNDP seeks to further shed light on gender differences and prevalent conditions of inequality in the context of advancing human development. Other indicators aim to present a more comprehensive assessment of conditions of poverty, which are linked to various forms of deprivation. This includes, for example, the multi-dimensional poverty index (MPI), which was developed by the Oxford Poverty and Human Development Initiative and further modified in collaboration with UNDP (see [1]). While cognizant of this complexity of human development indicators, we wanted to select a limited number of targets representing the SDGs in this cluster and quantifiable and suited for modelling.

For SDG1, it is clear that one indicator needs to be related to the objective of no one living in extreme poverty by 2030. A key question is how to define extreme poverty. As suggested in the SDG target, the World Bank global poverty line[2] is chosen as the threshold for 2030. As differences in the cost of living worldwide evolve, the global poverty line has been periodically updated to reflect these changes. Where Target 1.1 specifically mentions $1.25 per day, the World Bank has updated the absolute poverty line to $1.90 per day (US$ 2011). We use 2 US$ (US$ 2015) per capita per day for 2030 and 2050 for practical reasons – and kept it constant over the period (given the correction for inflation). Relative poverty is also included under SDG10 and discussed in the *Prosperity* cluster.

SDG3 aims at ensuring healthy lives. We view healthy life expectancy at birth as a summary indicator[3]. The set of SDG targets includes several other indicators, including maternal mortality rates, and many other indicators are also used in the literature. However, the advantage of the healthy life expectancy indicator is that it is all-encompassing. At the country level, an additional indicator is included of a minimum increase in healthy life expectancy at birth of 3 years per decade[3], which would be non-linear: countries with very low life expectancy at birth gain many years by saving infants' and children's lives, while countries with higher life expectancies show smaller gains as the lives saved postpone the age at death. The SDG target on under 5 mortality rate is used to track progress in developing countries. The SDG target level of 25 deaths per 1,000 live births is taken for 2030, further halved by 2050 to increase progress. Finally, alternative indicators that were considered include, among others, normal life expectancy at birth, a goal of avoiding 40% of premature deaths[4] and the median health-related SDG index used by the Global Burden of Disease study[5]. The latter, however, will require a much more comprehensive set of underlying indicators to be modelled.

SDG4 aims for quality education. The addition of universal secondary education expanded the Millennium Development Goals (MDGs) ambition, which targeted universal primary education only. This addition is based partly on recent insights that, for developing countries to come out of poverty, universal primary education is not enough and must be complemented by secondary education for broad segments of the population[6]. We chose the share of young people achieving lower secondary education as this covers the compulsory schooling time in most countries. Considering current enrollment rates in primary education, achieving 100% completion of lower secondary education by 2030 is practically impossible, so the target values proposed are 80% in 2030 and 100% in 2050. A supporting threshold is introduced of 100% primary completion rate in 2030. Alternative indicators may include literacy rates, expected years of schooling, participation in early childhood education, the share of the total population with lower secondary education, a measure of the quality of education through graduate employment and mean years of schooling.

SDG5 aims for gender equality. Out of the broad domains covered by this SDG, we chose education and income to track female empowerment. The target values aim at full equality in 2030 as called for by SDG5. While some models cover differences in education, the wage gap is addressed in very few models – and might only be a future alternative indicator. The advantage of the education-gap indicator is that it is directly related to future capacity and has an established link with other indicators such as fertility levels. Other indicators used to track current progress regarding gender equality include the female to male labour force participation rate, the proportion of women in national parliaments, the share of women in management roles, legal gender discrimination and rates of sexual violence. However, none of these is currently captured by integrated assessment models.

Table S1: Proposed indicators for the people domain and alternative indicators considered

SDG	*Proposed indicator*	*Alternative indicators considered*
1	• Number of people below the international poverty line	Different thresholds for absolute poverty line and dynamic change over time. Multi-dimensional poverty indicators have not been selected as the different elements (e.g. access to basic services are covered by other indicators)
3	• Healthy Life expectancy at birth (years) • Under 5 mortality rate (deaths per 1000 live births)	maternal mortality rates; normal life expectancy at birth, a goal of avoiding 40% of premature deaths[4] and the median health-related SDG index
4	• Share completing lower secondary education	literacy rates, expected years of schooling, participation in early childhood education, the share of the total population with lower secondary education, a measure of the quality of education, and mean years of schooling.
5	• Gender gap in mean years of schooling >aged 15 years) • Female estimated earned income over male	the female to male labour force participation rate, the proportion of women in national parliaments, the share of women in management roles, legal gender discrimination and rates of sexual violence

Prosperity (SDGs 8, 9, 10, and 11)

The cluster of SDGs 8, 9, 10 and 11 envisages societies and economies that offer a prosperous and fulfilling life.

SDG8 aims for sustained and inclusive economic growth and full and decent employment. As prosperity in high-income countries is no longer driven by economic growth per se[7], a focus is placed on sufficient economic growth in low and lower-middle-income countries, eventually leading to a convergence of living standards. We, therefore, propose an indicator of economic convergence as measured by the ratio of GDP/capita in the target country to the average OECD GDP/capita (both measured in PPP). This indicator reflects SDG target 8.1 (sustained per capita economic growth in accordance with national circumstances, including high growth rates in the least developed countries) as well as the overarching goal of inclusive growth across countries. Our quantitative targets are based on historical examples of rapid GDP/capita growth and income convergence, particularly the Asian "tiger economies" in the 1960-1995 period and China post-1990. In these cases, GDP/capita relative to the developed economies multiplied by a factor of ≥ 4 in a few decades, with per capita growth rates of ~7%[8].

As a 2050 target for our convergence indicator, we suggest a fourfold increase for low-income countries (translating the World Bank income classification thresholds into $ 2011 PPP; these are countries with a GDP/capita below ~6.5% of the average OECD value). As some countries start from around 2% of the OECD value, we supplement this with an additional threshold of reaching at least 15% of the OECD value in 2050. For lower-middle-income countries (in PPP below ~21% of the average OECD GDP/capita), we propose a threefold increase as a target for 2050. Assuming an average GDP/capita growth rate of 1.5% in OECD countries, these targets translate to annual GDP/capita growth rates of 6% in low-income and 5% in lower-middle-income countries over the period 2019-2050. For calculating the intermediate 2030 targets, we assume a 7% growth rate until 2030, declining by 1 percentage point each additional decade until 2050 in low-income countries and the same growth rate of 5% in lower-middle-income countries, leading to 2030 convergence factors of two for low-income and 1.5 for lower-middle-income countries. As an aside, we note that these targets will be met for many countries under an SSP1 GDP and population scenario[9].

The second proposed indicator for SDG8 is related to employment and decent work (targets 8.5-8.8). Work serves two essential purposes. It gives individuals access to financial income for entertaining a life of their choosing, and it provides meaning and organising structure to life. Possible changes in the future of work could mean that these two dimensions do not necessarily need to coincide in the same activity anymore. Therefore, for the achievement of SDG8, it will be essential to provide every human with a stable income stream that will be the accumulation from different sources (labour income, capital income, transfer income). In our target set, access to decent income is covered by a combination of per capita GDP convergence between countries (see above) and reduced income inequality within countries (see our choice of indicator for SDG10). In addition to a decent income, there needs to be sufficient availability of meaningful activities, i.e. decent employment opportunities or other activities of societal value such as caretaking or community service. We focus on employment as an indicator but acknowledge that the future of work is likely to change substantially with increasing digitalisation and automation[10]. We, therefore, may eventually require a broader notion of activities with economic or societal value to cover the goal of decent work. Following O'Neill et al. [3], we set a target of less than 6% of the labour force being unemployed (or more broadly being without valued activity). SDG8 also contains the fundamental goals of eradicating forced and child labour (target 8.7), protecting labour rights, and promoting a safe working environment (target 8.8). These fundamental goals are not singled out explicitly in our set of indicators. However, they are implied by a range of indicators relating to poverty eradication (SDG1), universal education (SDG4), broad access to socio-economic activities

(SDG9), decent income (SDG10) and living conditions (SDGs 3, 6, 7, 11), and gender equality (SDG5). Likewise, other targets of SDG8 relating to innovation (targets 8.2 and 8.3) and access to finance (targets 8.3. and 8.10) are largely covered by our choice of indicators for SDG9, and the target 8.4 on global resource efficiency is covered by SDG12 on sustainable production and consumption.

The indicators proposed for SDG9 aim to capture multiple aspects of infrastructure (both physical and non-physical) and innovation, focusing on technologies and services that can serve as key enablers. SDG 9.1 emphasises access to transport infrastructure to support economic development and human well-being. We adopt a broader concept of access to markets, knowledge and culture, both physically in terms of travel time to the nearest city and non-physically in terms of access to information and communications technologies (ICTs). As highlighted in SDG9, ICTs such as mobile phones and the Internet are key enabling technologies. We focus on Internet use (beyond mere access) here and adopt a near-universal internet use target among adults and teenagers, i.e. around 95% of the population, for 2030 and beyond (cf. SDG9). The target for physical access to market places and knowledge and culture hubs is based on the global map of travel time to the next city [11]. Following their definition of a city (a contiguous area with a population density above 1,500 km^{-2} or a built-up area with at least 50,000 inhabitants), we use the typical values in high-income countries as a motivation for setting our target for 2050: less than one hour for 90% of the population. This can be compared with the current situation in low-income countries where less than half of the population lives within one hour of the next city, and 20% of the population has to travel for more than three hours to the next city. For 2030 we propose an intermediate target of less than 3 hours travel time to the next city for 90% of the population in low-income countries, while middle and high-income countries should already have reached the long term target by 2030.

Another essential element for economic access is access to financial services. SDGs 9.3 and 8.3 focus on small and medium enterprises (SME) access to such services and their market integration. Here we widen the consideration of financial service access to individuals to cover the related SDG 8.10. As a simple proxy for broad access to financial services, we use the share of the population with an account at a financial institution, including access to mobile-money-services[12]. We choose a mid-century target of 95% account ownership among the adult population, reflecting near-universal access to financial services. For 2030, we suggest a target of 90% in middle and high-income countries, which mirrors current values in OECD countries and 80% of the adult population in low-income countries. The target should be reached in 2030 in middle and high-income countries and 2050 in low-income countries. Account ownership is a proxy indicator that focuses particularly on financial inclusion. Financial development is a broader concept that also takes into account the depth and efficiency of financial markets. We acknowledge that those factors are relevant for credit availability as highlighted in SDGs 8.3 and 9.3, but suitable and easily accessible indicators are hard to come by. There are attempts to include macro-level indicators such as credit to GDP ratio and other indicators into compound indices for financial development[13]. However, their direct relevance to the SDGs is less clear, and data availability is limited. In the SDG context, the finance gap for micro/small/medium enterprises (MSME) is a potentially relevant indicator for SDG9.3, but it is only available for emerging economies to date[14]. More work on SDG-oriented indicators for access to financial services is needed.

Besides infrastructure and services, a key focus of SDG9 is innovation as captured in SDG9.5, which calls for enhancing scientific research and increasing public and private research and development (R&D) investments. We adopt private and government-financed gross domestic R&D expenditure (GERD) in

per cent GDP as central indicators for R&D investments (cf. target 9.5.1). The target is set to 3% of GDP in 2030. This value is often used as a benchmark in country comparisons of R&D spending and was adopted as a target by the European Union[15]. Currently, OECD countries spend around 2.5% of their GDP on R&D.

Other elements of SDG9, such as specific goals for industry (target 9.2), have not been targeted explicitly as both industry and services will be nurtured by increased innovation and improved access to markets, knowledge and finance. Likewise, SDG target 9.4, which calls for increased resource efficiency and environmental soundness of industrial production, is covered mainly by SDG12. This allows us to limit the number of indicators for SDG9 to four, also covering aspects of SDG8. We note, however, that it remains a research challenge to better represent these indicators in future modelling efforts.

SDG10 calls for reducing inequality both across and within countries. The inequality dimension across countries is already covered by the income convergence indicator proposed for SDG8. For inequality within countries, we focus on relative poverty and use the OECD definition[16] of people living below half of the national median income (cf. target 10.2.1). While data for the Gini coefficient is more widely available than for the selected relative poverty indicator, the latter links more closely to the official indicator set and avoids some of the known issues of the Gini coefficient (such as being rather insensitive to the tails of the distribution[17]). To derive a quantitative target for this indicator, we examine national statistics for the Gini index taken from the World Development Indicators[18]. In recent years the lowest measured Gini indices are around 25, with around 15-20% of the countries with available data having Gini indices below 30. We, therefore, take a value of $\leq$30 as an ambitious but still realistic target to be reached by 2050. Under the assumption of a lognormal income distribution, we can analytically relate the Gini coefficient to our proposed indicator. This yields a target of at most 10% of the population living below half of the median income (independently of the average income level) in 2050. We propose an intermediate target of at most 15% of the population in relative poverty by 2030. These targets mandate a pathway of decreasing relative poverty for all countries, fulfilling SDG10.1 calling for sustained income growth of the bottom 40% of the population at a rate higher than the national average. There are also other relative poverty concepts[19], e.g., based on consumption patterns. Here we use relative income as a proxy for relative poverty and inequality within countries as it is most widely used and easily accessible. SDG1 targets absolute poverty. SDG10 includes a set of other goals on inclusion and equal opportunities for societal groups. Those are not explicitly mapped to indicators here as root causes are addressed by other SDGs, including the access indicators defined for SDG9.

SDG11 deals with sustainable cities and communities. Our selected indicators focus on two key aspects: adequate housing and a healthy urban environment. We represent the former by the fraction of the urban population living in slums, with a target of zero by 2050 and an intermediate target of less than 10% in 2030. While this intermediate target would not completely eliminate slums by 2030, it is nonetheless ambitious given recent t[17]rends[20]. The number of people living in slums is a useful composite indicator that already captures several important aspects of life in cities. Some of these dimensions are also cross-cutting with indicators from other SDGs, e.g. poverty (see SDG1), access to piped water (SDG6) or energy (SDG 7). Access to piped water and electricity can also serve as proxy indicators for the quality of housing and municipal planning and infrastructure services.

Our second indicator is the fraction of the urban population exposed to hazardous levels of air pollution, quantified by a threshold on the concentration of fine particulate matter (PM2.5) of 25 $\mu g/m^3$. The

threshold follows the upper value (24-hour mean) of the WHO guideline[21] (WHO, 2018) and coincides with the annual average threshold value used by the EU. As targets, we propose that less than 10% of the urban population be exposed to higher annual average levels of PM2.5 by 2050 and less than 20% by 2030. These values are comparable to current values in the EU[22]. Similar fractions are also obtained in SSP1-2.6W/m^2 projections[23]; note that the latter refers to the total population and not the urban population used here (making them less ambitious).

Clearly, two indicators can never fully capture the multi-faceted nature of life in cities. However, we argue that our selection, combined with those already covered in other SDGs, captures many essential dimensions. We further note that data on these indicators are readily available, making it easy to track progress.

Table S2: Proposed indicators for the prosperity domain and alternative indicators considered

SDG	*Proposed indicator*	*Alternative indicators considered*
8	Unemployment rate (formal economy)	Labor participation rate; Further expansion of the notion of work/meaningful contribution to society; child labour
	GDP/ capita compared to average OECD GDP/capita	International gini index, other thresholds
9	private and government-financed gross domestic R&D expenditure (GERD) in per cent GDP	Comparison with required R&D levels; R&D investment rates
	Proportion of population using the internet (%)	
	Proportion of adult population with access to finance	
	Travel time to the nearest city	
10	Number of people with <50% of national median income	Income growth rate of bottom 40% compared to the national average (SDG target 10.1)
11	Population living in slums (urban)	The air pollution indicator could be based on more air pollutants and use alternative targets. For housing, it might be possible to define more advanced quality indicators to go beyond the most basic level (slums)
	Pop. exposed to annual average PM2.5 >25µg/m^3[51]	

Planet integrity (SDGs 13, 14, and 15)

The SDGs on climate action and aquatic and terrestrial biodiversity relate to the condition of the natural environment and the planetary boundaries[24,25]. Given the ongoing work on the Planetary Boundary framework, we have decided to look for synergy for some indicators and goals. For SDG13, we follow the target of the Paris Agreement, i.e. well below 2°C and pursue efforts to stay below 1.5°C. Global IAMs models can use this target directly. However, other models (e.g. at the national scale) need derived information, such as existing IAM *emission profiles*[26] or national carbon budgets over a specific period. We have selected a greenhouse gas emission target – but did not specify exactly the downscaling method. Moreover, we left it up to the user to interpret the Paris Agreement concerning the temperature goals and only set an upper bound. Future work could further specify this target. The target for ocean acidification (SDG14) is also related to CO_2 emissions and is, for that reason, assumed to be covered by the climate target. In addition, for SDG14, eutrophication can be covered by the

phosphorous flow from freshwater systems into the ocean (based on the planetary boundaries) or the index of coastal eutrophication (selected from the SDGs)[27]. The latter is more refined but does need further modelling of coastal systems.

Further, the fraction of fish stocks within safe biological limits[28] represents the sustainable use of fish resources[24]. We also considered the Ocean Health index – or other work on biodiversity indicators for aquatic systems (such as the mean species abundance). However, we considered work not advanced enough to add them at this stage, given the relatively complicated calculation schemes. For terrestrial biodiversity, in principle, multiple dimensions of biodiversity would need to be covered[29]. In order to limit the number of targets, however, the planetary boundary indicators are proposed, i.e. the minimum extent of forest cover in different forest biomes, the balance of nitrogen into soils, and the biodiversity intactness index (BII)[30]. For the latter, alternative aggregated biodiversity indicators exist and possibly a comparison project can show whether these can be used as a replacement (if applied relative to reference year).

Table S3: Proposed indicators for the planet integrity domain and alternative indicators considered

SDG	*Proposed indicator*	*Alternative indicators considered*
13	Paris goals	National carbon budgets over a specific period; or emissions levels. Alternatively, one could also look at means indicators related to non-GHG emitting energy sources or indicators related to climate impacts, such as the number of deaths from natural disasters or sea-level rise.
14	P flow from freshwater systems into the ocean the proportion of fish stocks within biologically sustainable levels[56]	Index of coastal eutrophication Ocean Health Index Mean species abundance
15	global: area of forested land as % of original forest cover Biome: area of forested land as % of potential forest Industrial and intentional biological fixation of N Biodiversity Intactness Index (BII)	Other aggregated biodiversity indicators such as species abundance.

Key resources (SDGs 2, 6, 7 and 12)

Access to resources forms an essential aspect of sustainable development, while at the same time, these resources need to be properly maintained. Key resources include energy, food and water – while SDG12 deals with the consumption and production of resources in general. SDG2 focuses on both ending hunger and promoting sustainable agriculture practices. The first indicator is the number of undernourished people (proposed by many other publications, including [3]). The target of 0 people undernourished by 2030 is taken from the SDG and needs to be sustained beyond 2050. As the threshold for undernourishment, we apply the minimum daily energy requirement (MDER, kcal/cap/day) suggested by FAO (2017). FAO (2017) calculates country-specific minimum daily energy requirements.

The 2030 and 2050 global average minimum thresholds are based on calculations by Hasegawa for SSP1 [31]. The future mean MDER is calculated for each year and country using the mean MDER in the base year at the country level[26], adjustment coefficient for the MDER in different age and sex groups[27] and the future population demographics[28] to reflect differences in the MDER across age and sex [31]. As SDG2 also covers malnourishment, the prevalence of malnourishment and stunting and wasting could also be included. In general, reflecting the nutrient value of the diet, beyond mere energy content (kcal), moving towards reflecting healthy diets for all should be a goal for modelling. This is an active area of international research[32,33]. We also added an indicator related to obesity. Obesity is on the rise globally, also in developed countries, and has severe health impacts (linked to SDG3), but also clear links to consumption patterns (SDG12) and the overall impact of the agriculture system on the environment (also given the role of animal products). Work on diets in relation to sustainable development (e.g. EAT-Lancet Commission) and as well as health impacts (non-communicable diseases) is evolving[34] but setting target values and related thresholds still poses a challenge as it closely connected with lifestyle and the goal would be to avoid diseases. SDG2 also covers agriculture and food production. An indicator of sustainable agriculture could be considered as well. However, this partly links to (end-goal) indicators proposed under the environmental SDGs (13, 14 and 15). These automatically provide guardrails relevant to sustainable agriculture practices. Therefore, it is not added here.

SDG6 covers water demand by human beings and the environment. The first indicators look at access to clean water. We use a threshold of sufficient access 50l/per/capita/day recommended as basic water requirement[35]. This is proposed as a universal threshold focusing on meeting basic needs, including water for drinking, basic sanitation, plus some water for cooking and bathing. The second indicator is access to sanitation services. Finally, for water scarcity, we use the proportion of an area or region under water stress. Here, water stress is defined as the ratio between total water use and availability. A value above 40% is defined as areas suffering from severe water stress. It is essential to calculate a total balance (including water use from groundwater and environmental water needs) and water availability (including sustainable groundwater availability, lakes, and technical solutions like desalination). This points at groundwater over-use particularly and some lakes and surface waters that are contracting in size/volume. It should be noted that the indicator is also strongly dependent on natural attributes. Other indicators considered include total water use (as in the planetary boundaries framework[24]), the number of people living in water-scarce areas, environmental flows in freshwater ecosystems and water quality. However, these indicators contain less actionable information or are more challenging to model in an integrative assessment framework.

SDG7 calls for both access to energy for all and the sustainable use of energy. We propose to focus on energy service levels (final energy demand), including heating/cooling and mobility service per household per day that allows a decent life (see [36]), going beyond mere access. What is deemed “decent” is subject to national circumstances (e.g. also related to climate zone). Because of advances in technology and living standards, energy requirements in 2050 are subject to change.

For SDG12, a range of indicators can be considered. Our selected indicators – Food loss and waste and Municipal material recovery – only cover a subset of the relevant resources involved in society’s production and consumption processes. Target values will have to be even more ambitious in the long run. However, they can be regarded as illustrative of the capabilities of society to manage and recycle resource flows. These indicators are also well established - at least in industrialised countries - in statistical reporting and can be captured in a modelling framework at least in a stylised way

(technologies, economic incentives). Suitable alternatives could be more comprehensive indicators and indices such as the human appropriation of natural primary productivity (HANNP)[3], the ecological footprint, the material footprint, the global food loss index or recycling rates, but these indicators are hardly covered by models yet. Further development could also focus more on circular economy indicators and overall efficiency.

Table S4: Proposed indicators for the key resources domain and alternative indicators considered

SDG	*Proposed indicator*	*Alternative indicators considered*
2	• Number of people undernourished • Number of people with obesity	• Possible indicators related to the prevalence of malnourishment and stunting and wasting, reflecting the quality of the diet, beyond mere energy content (kcal), • Diet indicators comparing to recommended diets – possibly including planetary considerations) (not used yet as indicators would need to be developed). • Meat consumption • Indicators reflecting sustainable agriculture (not included because these are already captured mostly via other SDGs)
6	• Population without access to improved water source piped • Population without access to improved sanitation facility • Area under water stress (water stress index for most water-scarce month/season)	• water-scarce areas, • environmental flows in freshwater ecosystems • water quality indicators
7	• Population cooking with traditional biomass • Population without basic electricity access	• Indicators focusing on energy service levels, including heating/cooling and mobility service per household per day that allows a decent life (see [36]), going beyond mere access
12	• Food loss and waste • Municipal material recovery	• human appropriation of natural primary productivity (HANNP)[3], • the ecological footprint, • material footprint indicators, or other Indicators related to net primary material use • global food loss index • recycling rates

Peace, Institutions and Implementation (SDGs 16 and 17)

Compared to other SDG areas, the definition of lean and evidence-based benchmarks for SDGs 16 and 17 seems more challenging because of the contingent nature of governance, politics and peace. However, measuring these issues is not only possible but quite common. The use of quantified and standardised measures of governance, political institutions and violent conflict has become ubiquitous and common practice in political sciences and conflict research. We propose a series of numeric targets based on the insights from empirical studies and normative considerations of minimal quantifications of the political goals enshrined in the SDGs. Improving a list of indicators for SDGs 16 and 17 is a challenge, which the broader social science community has acknowledged since 2015. However, quantitatively

projecting long-term scenarios of governance[37,38] and political events such as violent conflict[39-41], coups[42,43], and regime change[44] are rising. It will require more engagement with social science communities interested in future scenarios to further advance the indicators and their application for integrated modelling.

The proposed indicators for the target space approximate the more extensive set of targets in both SDG16 and 17 while being sufficiently narrow to allow quantitative modelling of pathways. They address some of the most critical interlinkages to other goals, particularly SDG4, 5, and 10. We focus on measurable political and financial outcomes of institutions instead of the latter's procedural attributes as proposed in some of the targets. This is based on the assumption that there is a significant correlation between institutions and outcomes linked to institutions. For instance, participatory political institutions are more likely to provide inclusive policies. In addition, political institutions are better to predict because they are more stable over time than contingent political events.

Peaceful, just, and inclusive societies (SDG16) and global partnership (SDG17) are desired outcomes of the 2030 Agenda and serve as essential enablers to achieve the remaining SDGs[45,46]. SDG16 and 17 describe the political goals defined by Agenda 2030. SDG16 calls to significantly reduce all forms of violence, promote peace and build effective, accountable and inclusive institutions. Armed conflicts with high fatality numbers are known to perpetuate underdevelopment[47]. Accordingly, the high number of conflict-related deaths in recent years need to be reduced drastically if SDGs shall be achieved, especially in fragile states and conflict regions. Current trends indicate that the number of violent deaths has been increasing since 2005. SDG target 16.1 also aims to reduce violent crime. However, we propose the number of armed conflict fatalities as an indicator for two reasons. First, armed conflict can drastically undermine or even reverse the development of the overall SDG agenda on a national or regional level. Moreover, in contrast to violent crime, global conflict fatality estimates are readily available in a standardised form dating back several decades. In contrast, e.g. homicide rates are often missing in the least developed countries during many years in the past, making global modelling challenging. While we endorse statistics of violent crime as a suitable measure for regionally restricted analyses, we propose fatalities from armed conflict as our preferred, globally available measure of the most severe form of insecurity. We choose a normative goal in line with the formulation of goal 16 and expect 0-fatalities by 2030 and 2050. Although this is not feasible globally, it is more likely on the country-level.

Beyond the absence of violence, strong, responsive and representative political institutions are central preconditions for sustainable development and (positive) peace[48,49]. We use the term "institutions" and not the term "governance" (which is more common in the context of sustainability research) for two reasons. First, institutions are structures that shape human behaviour. Being a "sticky concept", institutions are highly path-dependent and, thus, only change slowly over time[50]. Second, political institutions, as we measure them, are state-centred. We assume that states and their subordinate units from the national to local level are the only actors who can make binding decisions for the public. In contrast, governance is a concept that refers to different forms of processes and decision-making, which do not necessarily include state institutions[51]. For instance, governance can refer to a network of civil society actors that shape public debates or a board of an enterprise. We propose to measure these institutional aims using two indices. The Equality Before the Law and Individual Liberty Index[52] broadly captures target 16.3 ("Promote the rule of law [...] and ensure equal access to justice for all") as well as the protection of fundamental freedoms (target 16.10). Furthermore, the index includes information on

torture, i.e. it captures the most severe violation of SDG16.2. Beyond these specific goals, improvements on this index correlate with decreases in corruption (target 16.5) and effective and transparent institutions (target 16.6)[53]. Alongside more effective institutions, we can expect a reduction in crime (target 16.4), and states should provide a legal identity to all, including birth registrations (target 16.9). The second proposed measure, the Equal Access Index[52], describes whether all social groups "enjoy equal *de facto* capabilities to participate, to serve in positions of political power, to put issues on the agenda, and to influence policymaking" [52] (target 16.7). In line with previous research, we expect that political equality decreases economic and social inequalities and, thus, has positive effects on achieving SDG10 ("Reduce inequality in and among countries").

Given that both proposed indices are continuous, it is an empirical challenge to identify a threshold that classifies when the political goals of the SDGs are achieved. We used the following steps to define quantified and empirically grounded thresholds for each index:

- First, we used the fact that each index is based on a more extensive set of individual, ordinal items that describe specific conditions in countries worldwide. We qualitatively identify the ordinal answer categories for each item, which capture the normative goals enshrined in SDG16. Tables S1 and S2 outline for each index the content of each item, the available ordinal categories, and the categories that we consider to be in line with the goals of SDG16.
- Second, we draw on V-Dem's empirical measurement of each item's most likely ordinal value ("_ord" variables reported by V-Dem). Using this measurement, we extract for each index all country-years that reached (or exceeded) *on all items of the index* the respective ordinal category identified in step 1. This leaves us for each item with the precise subset of countries that, according to V-Dems measurement, fulfilled all conditions outlined by SDG16 in a given year.
- Third, within this subset of country-years, we then calculate each index's lowest empirically estimated index score.

We suggest these index scores as the minimum index score, which describe a situation in which the normative targets in SDG16 are likely to be reached and propose them as our empirically derived threshold values. We call these values the *minimal empirical index score, which captures a situation that reflects SDG 16's targets*.

The target related to SDG 17 raises various aspects, including finance (SDG 17.1- 17.5), technology (17.6-17.8), capacity building (17.9), Trade (17.10-17.12), policy and institutional coherence (17.13-17.15), multi-stakeholder partnerships (17.16- 17.18), data, monitoring and accountability (17.18- 17.19). Our approach is to capture aspects in SDG 17 related indicators that can be considered preconditions and fundamental means of implementation to initiate, scale-up and monitor efforts to achieve targets defined in other SDGs. The idea is that if the listed minimal thresholds are in place, all actors (governmental and non-governmental) will be able to contribute to the achievement of the comprehensive SDG Agenda. Based on this reasoning, we choose financial resources of the state, statistical capacity and civil society networks. First, pinpointing an adequate revenue level is difficult. It is important to highlight that this is not about imposing the idea of a comprehensive welfare state on all countries but about identifying a state that has sufficient financial means to implement policies towards the achievement of the SDGs. We use total government revenue without natural resources as an indicator to measure domestic resource mobilisation. We use the global average for a five year period

(2011-2015)[54]. We expect countries below this threshold to increase their domestic resource by 20% in 2030, including the extraction of natural resources. This is based on the assumption that countries, which rely on natural resources, will not be able to diversify and restructure their economies until 2030. Until 2050, the level of 2030 shall be maintained but without including revenues generated by natural resources. Second, the SDG process not only demands increasing efforts in different areas but also proceeding differently and learning from past experiences to increase effectiveness and efficiency in reaching the goals. In this context, the availability of good statistics is crucial. Here we consider that there should not be any compromises, and all countries should have the key statistical information available. To measure statistical capacity, we use "source data", the second dimension of the World Bank's statistical capacity score, which indicates whether a country collects data frequently, according to international standards and whether data is available and reliable[18]. To define thresholds for this indicator, we take a maximalist approach.

By 2030 we expect all countries to achieve the highest possible score. In 2050, the same threshold applies but statistical capacities shall be completely self-financed. Third, focusing on civil society and the degree to which it is dense and inclusive at the international level is crucial for the success of the SDG Agenda and a cornerstone of the philosophy behind it. We assume that the number of international non-governmental organisations of which a country is a member indicates whether a society is globally interconnected[55]. Based on the Handbook of the Union of International Associations, we take the first quartile (2017) value as a threshold. Countries that do not meet this threshold by 2017 shall achieve it by 2030. In 2050, the value shall increase above the 25th percentile based on the 2030 data.

We rule out some of the indicators proposed in the UN global indicator framework for SDGs for the following reasons. Official Development Assistance (ODA) will certainly play a role in supporting the achievement of various goals. For two main reasons, we consider that it is better to leave ODA out of the model. Although ODA remains an important resource for many developing countries, its relevance – compared to other sources such as own generate domestic revenue, private flows and remittances – is expected to decrease in the future[56.] Also, with regard to many of the indicators, ODA can be expected to contribute to their achievement but not as the only factor. Good examples are two of the indicators we propose: Revenue collection and statistical capacity. ODA definitely plays a role in this, too, but in the medium and long term, the goal is that the capacity in developing countries is developed and the levels are maintained without aid. This rationale also makes us differentiate between the threshold for 2030 and 2050. While until 2030, we expect ODA to be crucial in achieving the threshold. In 2050, we expect countries to maintain the threshold set for 2030 on their own, without external support.

Technology related aspects are partly captured in SDG 9 (Internet access), and the overall goals of enhancing cooperation and knowledge sharing are captured partly in our indicator on international networks. The same argument holds for SDG goals 17.9 and 17.13 to 17.18. We assume that the philosophy of these goals is well captured by the indicator on international networks. Trade is not included explicitly in the list of indicators that we propose. Certainly, an open, rules-based trade system can strengthen SDG implementation. In fact, if the increasing trend towards protectionism consolidates, this can be expected to have a major negative effect on achieving SDG goals, especially through reduced economic growth and price stability[57]. This is quite certain in the mid and long term but less so in the short run. Furthermore, as the SDG Knowledge Platform itself indicates, context is key and "[t]rade liberalisation and globalisation can have both positive and negative effects on sustainable development. There is a continued need to support efforts by developing countries to integrate themselves into and

derive benefits from the multilateral trading system. At the same time, attention also must be given to enhancing the contribution of the multilateral trading system to sustainable development" (https://sustainabledevelopment.un.org/topics/trade). In this sense, the philosophy of the trade-related goals in the SGD Agenda goes beyond the goal of more trade or fewer tariffs but include the capacity to trade in a way that is compatible with other goals in the SDG system (see, for instance, SDG 14.6 on fisheries). Finding indicators that respect this sustainability perspective is difficult, and assume that those that might satisfy the demand to capture negative externalities are too narrow in scope.

Table S5: Proposed indicators for the peace, institutions and implementation domain and alternative indicators considered

SDG	*Proposed indicator*	*Alternative indicators considered*
16	Battle-related deaths and fatalities from violence Equality before the law and individual liberty index ‡ Equal access index ‡	Number of victims of intentional homicide indicator (data not reliable) Individual perceptions of security are a relevant indicator (no cross-national data available) Corruption index (perception data with social desirability bias) Illicit financial flows (data not reliable) Outcome indicators for government performance (high correlation with other SDG, for instance, health, poverty)
17	Statistical Capacity score Total government revenue Member of international NGOs	State capacity on different levels (lack of data) Tax expenditure, Official Development Assistance (ODA), remittances and trade balance, investment flows and debt service Amount of public-private partnerships

Note S2: Connection between selected indicators and the six transformations

TWI2050 has identified six fundamental transformations, describing a set of interventions for simultaneously achieving the SDGs and extending sustainable development beyond 2030: i) advancing human capacities and demography, ii) establishing responsible consumption and production patterns, iii) achieving decarbonisation and inclusive and sustainable energy systems, iv) establishing sustainable land use management and access to food while safeguarding biodiversity of terrestrial and aquatic ecosystems, iv) developing sustainable cities and communities and vi) aligning the digital revolution with the SDGs[57]. In Table S6 we link the selected indicators of the target space to these transformations. Grey shading indicates the relevance of the target for the difference transformations (dark grey directly coupled; light grey important). Governance and capacity-building are enablers and framed as "cross-cutting" issues of the six transformations. While achieving SDG 16 and 17 are clearly part of the first transformation (human capacity), SDG 16 and 17 work as enablers for the other five transformations. This approach is also in line with the rationale of Agenda 2030.

Table S6: Connection between selected indicators and the six transformations

SDG	TWI2050 normative goal	Indicator	Human capacity & demography	Responsible consumption/production	Decarbonization and energy	Food, biosphere & water	Sustainable cities & communities	Digital revolution
1	*End extreme poverty*	Number of people below international poverty line						
2	*End hunger*	Number of people undernourished						
	Healthy diets for all	Number of people with obesity						
3	*Achieve adequate health care for all*	Healthy Life expectancy at birth (years)						
		Under 5 mortality rate (deaths per 1000 live births)						
4	*Universal lower secondary education*	Share completing lower secondary education						
5	*End gender discrimination in education*	Gender gap in mean years of schooling >aged 15 years)						
	Achieve gender pay parity	Female estimated earned income over male						
6	*Universal access to clean water*	Population without access to improved water source piped						
	Universal access to sanitation	Population without access to improved sanitation facility						
	End water scarcity	Area under water stress (water stress index for most water-scarce month/season)						
7	*Universal modern energy services for all*	Population cooking with traditional biomass						

		Population without basic electricity access						
8	*Work for all*	Unemployment rate (formal economy)						
	Global economic convergence	GDP/ capita compared to average OECD GDP/capita						
8	*R&D*	R&D intensity in per cent GDP						
	Universal access to ICT	Proportion of population using the internet (%)						
	Universal access to finance	Proportion of adult population without access to finance						
	Fast access to an economic hub	Travel time to the nearest city						
10	*Decrease relative poverty*	Number of people <50% of median national daily income						
11	*Decent housing for all*	Population living in slums (urban)						
	Improve air quality in cities	Pop. exposed to annual average PM2.5 >25µg/m^{3}[51]						
12	*Reduce waste & pollution*	Food loss and waste						
		Municipal material recovery						
13	*Limit global warming*	Paris goals						
14	*Balance phosphorus in oceans*	P flow from freshwater systems into the ocean						
	Sustainably manage marine resources	Proportion of fish stocks within biologically sustainable levels[56]						
15	*Halt Land-system change (deforestation)*	Global: area of forested land as % of original forest cover						
		Biome: area of forested land as % of potential forest						
	Balance nitrogen in soils	Industrial and intentional biological fixation of N						
	Protect biodiversity	Biodiversity Intactness Index (BII)						
16	*Reduce violence and related deaths*	Battle-related deaths and fatalities from violence						
	Promote the rule of law and ensure equal access to justice for all	Equality before the law and individual liberty index ‡						

	Ensure resp., incl., participatory and repres. decision-making	Equal access index ‡						
17	*Increase statistical capacities*	Statistical Capacity score						
	Strengthen domestic resource mobilisation	Total government revenue						
	Enhance interconnection with global civil society	Member of international NGOs						

Note S3: Application of target space to the SSP scenarios

Table S7: Origin of data used to show SSP2 performance

Target space indicator	Implementation
SDG1: #People in absolute poverty	The data on income distribution in the different SSPs could be used to calculate the number of people below 2$ per person per day[58]
SDG2: #People suffering from hunger	The was directly reported by the AIM model and has been later also reported by multiple model studies (AIM data is used here)[59]
SDG3: <5 mortality	The data is available from the original population scenarios of the SSPs[60].
SDG3: Total fertility rate	The data is available from the original population scenarios of the SSPs[60].
SDG4: #People w/o. sec. education	The data is available from the original population scenarios of the SSPs[60].
SDG5: Schooling gender gap	The data is available from the original population scenarios of the SSPs[60].
SDG6: Area under water stress	Water stress indicators have been calculated for the SSPs by multiple teams. Here, the data of Byers et al. is used[61]
SDG6: #People w/o san/clean water	Data based on SSP2[62]
SDG7: #people w/o access clean cooking	Access to clean cooking was based on data from the IMAGE team but is also reported by other IAM models
SDG7: #people w/o access electricity	Access to electricity was based on data from the IMAGE team but is also reported by other IAM models
SDG10: #people in relative poverty	The data on income distribution in the different SSPs could be used to calculate the number of people below 2$ per person per day[58]
SDG11: #people poor air quality	Air quality data for the SSPs was reported Rao et al. [63]
SDG13: CO_2 emissions	Data from the marker scenario of the SSP database were used[64]
SDG15: Loss of forest cover	Emissions from the marker scenario of the SSP database were used[64]

Note S4: More detailed description of some information used in the peace, institution and implementation domain

Table S8: Questions contained in the *Equal Access Index* and SDG-conformable target categories

V-Dem variable name	Question + answer categories	Clarification (according to V-Dem codebook V 7.1 - July 2017)	SDG-conformable target categories
v2pepwrgen	Is political power distributed according to gender? 0: Men have a near-monopoly on political power. 1: Men have a dominant hold on political power. Women have only marginal influence. 2: Men have much more political power but women have some areas of influence. 3: Men have somewhat more political power than women. 4: Men and women have roughly equal political power.	/	4
v2pepwrsoc	Is political power distributed according to social groups? 0: Political power is monopolised by one social group comprising a minority of the population. This monopoly is institutionalised, i.e., not subject to frequent change. 1: Political power is monopolised by several social groups comprising a minority of the population. This monopoly is institutionalised, i.e., not subject to frequent change. 2: Political power is monopolised by several social groups comprising a majority of the population. This monopoly is institutionalised, i.e., not subject to frequent change. 3: Either all social groups possess some political power, with some groups having more power than others; or different social groups alternate in power, with one group controlling much of the political power for a period of time, followed by another – but all significant groups have a turn at the seat of power. 4: All social groups have roughly equal political power or there are no strong ethnic, caste, linguistic, racial, religious, or regional differences to speak of. Social group characteristics are not relevant to politics.	A social group is differentiated within a country by caste, ethnicity, language, race, region, religion, or some combination thereof. (It does not include identities grounded in sexual orientation or socio-economic status.) Social group identity is contextually defined and is likely to vary across countries and through time. Social group identities are also likely to cross-cut, so that a given person could be defined in multiple ways, i.e., as part of multiple groups. Nonetheless, at any given point in time there are social groups within a society that are understood - by those residing within that society – to be different, in ways that may be politically relevant.	3 ; 4
v2pepwrses	Is political power distributed according to socio-economic position? 0: Wealthy people enjoy a virtual monopoly on political power. Average and poorer people have almost no influence. 1: Wealthy people enjoy a dominant hold on political power. People of average income have little say. Poorer people have essentially no influence. 2: Wealthy people have a very strong hold on political power. People of average or poorer income have some degree of influence but only on issues that matter less for wealthy people. 3: Wealthy people have more political power than others. But people of average income have almost as much influence and poor people also have a significant degree of political power. 4: Wealthy people have no more political power than those whose economic status is average or poor. Political power is more or less equally distributed across economic groups.	All societies are characterised by some degree of economic (wealth and income) inequality. In some societies, income and wealth are distributed in a grossly unequal fashion. In others, the difference between rich and poor is not so great. Here, we are concerned not with the degree of social inequality but rather with the political effects of this inequality. Specifically, we are concerned with the extent to which wealth and income translates into political power.	3 ; 4

Table S9: Questions contained in the Equality before the law and individual liberties Index and SDG-conformable target categories

V-Dem variable name	Question + answer categories	Clarification (according to V-Dem codebook V 7.1 - July 2017)	SDG-conformable target categories
v2clrspct	Are public officials rigorous and impartial in the performance of their duties? 0: The law is not respected by public officials. Arbitrary or biased administration of the law is rampant. 1: The law is weakly respected by public officials. Arbitrary or biased administration of the law is widespread. 2: The law is modestly respected by public officials. Arbitrary or biased administration of the law is moderate. 3: The law is mostly respected by public officials. Arbitrary or biased administration of the law is limited. 4: The law is generally fully respected by the public officials. Arbitrary or biased administration of the law is very limited.	This question focuses on the extent to which public officials generally abide by the law and treat like cases alike, or conversely, the extent to which public administration is characterised by arbitrariness and biases (i.e., nepotism, cronyism, or discrimination). The question covers the public officials that handle the cases of ordinary people. If no functioning public administration exists, the lowest score (0) applies.	3 ; 4
v2cltrnslw	Are the laws of the land clear, well publicised, coherent (consistent with each other), relatively stable from year to year, and enforced in a predictable manner? 0: Transparency and predictability are almost non-existent. The laws of the land are created and/or enforced in completely arbitrary fashion. 1: Transparency and predictability are severely limited. The laws of the land are more often than not created and/or enforced in arbitrary fashion. 2: Transparency and predictability are somewhat limited. The laws of the land are mostly created in a non-arbitrary fashion but enforcement is rather arbitrary in some parts of the country. 3: Transparency and predictability are fairly strong. The laws of the land are usually created and enforced in a non-arbitrary fashion. 4: Transparency and predictability are very strong. The laws of the land are created and enforced in a non-arbitrary fashion.	This question focuses on the transparency and predictability of the laws of the land.	3 ; 4
v2clacjstm	Do men enjoy secure and effective access to justice? 0: Secure and effective access to justice for men is non-existent. 1: Secure and effective access to justice for men is usually not established or widely respected. 2: Secure and effective access to justice for men is inconsistently observed. Minor problems characterise most cases or occur rather unevenly across different parts of the country. 3: Secure and effective access to justice for men is usually observed. 4: Secure and effective access to justice for men is almost always observed.	This question specifies the extent to which men can bring cases before the courts without risk to their personal safety, trials are fair, and men have effective ability to seek redress if public authorities violate their rights, including the rights to counsel, defense, and appeal. This question does not ask you to assess the relative access to justice men and women. Thus, it is possible to assign the lowest possible score to a country even if men and women enjoy equal – and extremely limited – access to justice.	3 ; 4

v2clacjstw	Do women enjoy equal, secure, and effective access to justice? 0: Secure and effective access to justice for women is non-existent. 1: Secure and effective access to justice for women is usually not established or widely respected. 2: Secure and effective access to justice for women is inconsistently observed. Minor problems characterise most cases or occur rather unevenly across different parts of the country. 3: Secure and effective access to justice for women is usually observed. 4: Secure and effective access to justice for women is almost always observed.	This question specifies the extent to which women can bring cases before the courts without risk to their personal safety, trials are fair, and women have effective ability to seek redress if public authorities violate their rights, including the rights to counsel, defense, and appeal. This question does not ask you to assess the relative access to justice men and women. Thus, it is possible to assign the lowest possible score to a country even if men and women enjoy equal – and extremely limited – access to justice.	3 ; 4
v2clprptym	Do men enjoy the right to private property? 0: Virtually no men enjoy private property rights of any kind. 1: Some men enjoy some private property rights, but most have none. 2: Many men enjoy many private property rights, but a smaller proportion enjoys few or none. 3: More than half of men enjoy most private property rights, yet a smaller share of men have much more restricted rights. 4: Most men enjoy most private property rights but a small minority does not. 5: Virtually all men enjoy all, or almost all property rights.	Private property includes the right to acquire, possess, inherit, and sell private property, including land. Limits on property rights may come from the state (which may legally limit rights or fail to enforce them); customary laws and practices; or religious or social norms. This question concerns the right to private property, not actual ownership of property. This question does not ask you to assess the relative rights of men and women. Thus, it is possible to assign the lowest possible score to a country even if men and women enjoy equal – and very minimal – property rights.	5
v2clprptyw	Do women enjoy the right to private property? 0: Virtually no women enjoy private property rights of any kind. 1: Some women enjoy some private property rights, but most have none. 2: Many women enjoy many private property rights, but a smaller proportion enjoys few or none. 3: More than half of women enjoy most private property rights, yet a smaller share of women have much more restricted rights. 4: Most women enjoy most private property rights but a small minority does not. 5: Virtually all women enjoy all, or almost all, property rights.	Private property includes the right to acquire, possess, inherit, and sell private property, including land. Limits on property rights may come from the state (which may legally limit rights or fail to enforce them); customary laws and practices; or religious or social norms. This question concerns the right to private property, not actual ownership of property. This question does not ask you to assess the relative rights of men and women. Thus, it is possible to assign the lowest possible score to a country even if men and women enjoy equal – and very minimal – property rights.	5
v2cltort	Is there freedom from torture? 0: Not respected by public authorities. Torture is practiced systematically and is incited and approved by the leaders of government. 1: Weakly respected by public authorities. Torture is practiced frequently but is often not incited or approved by top leaders of government. At the same time, leaders of government are not actively working to prevent it. 2: Somewhat. Torture is practiced occasionally but is typically not approved by top leaders of government. 3: Mostly respected by public authorities. Torture is practiced in a few isolated cases but is not incited or approved by top government leaders. 4: Fully respected by public authorities. Torture is non-existent.	Torture refers to the purposeful inflicting of extreme pain, whether mental or physical, with an aim to extract information or intimidate victims, who are in a state of incarceration. Here, we are concerned with torture practiced by state officials or other agents of the state (e.g., police, security forces, prison guards, and paramilitary groups).	4

v2clkill	Is there freedom from political killings? 0: Not respected by public authorities. Political killings are practiced systematically and they are typically incited and approved by top leaders of government. 1: Weakly respected by public authorities. Political killings are practiced frequently and top leaders of government are not actively working to prevent them. 2: Somewhat respected by public authorities. Political killings are practiced occasionally but they are typically not incited and approved by top leaders of government. 3: Mostly respected by public authorities. Political killings are practiced in a few isolated cases but they are not incited or approved by top leaders of government. 4: Fully respected by public authorities. Political killings are non-existent.	Political killings are killings by the state or its agents without due process of law for the purpose of eliminating political opponents. These killings are the result of deliberate use of lethal force by the police, security forces, prison officials, or other agents of the state (including paramilitary groups).	4
v2clslavem	Are adult men free from servitude and other kinds of forced labor? 0: Male servitude or other kinds of forced labor is widespread and accepted (perhaps even organised) by the state. 1: Male servitude or other kinds of forced labor is substantial. Although officially opposed by the public authorities, the state is unwilling or unable to effectively contain the practice. 2: Male servitude or other kinds of forced labor exists but is not widespread and usually actively opposed by public authorities, or only tolerated in some particular areas or among particular social groups. 3: Male servitude or other kinds of forced labor is infrequent and only found in the criminal underground. It is actively and sincerely opposed by the public authorities. 4: Male servitude or other kinds of forced labor is virtually non-existent.	Involuntary servitude occurs when an adult is unable to quit a job s/he desires to leave – not by reason of economic necessity but rather by reason of employer's coercion. This includes labor camps but not work or service which forms part of normal civic obligations such as conscription or employment in command economies.	4
v2clslavef	Are adult women free from servitude and other kinds of forced labor? 0: Female servitude or other kinds of forced labor is widespread and accepted (perhaps even organised) by the state. 1: Female servitude or other kinds of forced labor is substantial. Although officially opposed by the public authorities, the state is unwilling or unable to effectively contain the practice. 2: Female servitude or other kinds of forced labor exists but is not widespread and usually actively opposed by public authorities, or only tolerated in some particular areas or among particular social groups. 3: Female servitude or other kinds of forced labor is infrequent and only found in the criminal underground. It is actively and sincerely opposed by the public authorities. 4: Female servitude or other kinds of forced labor is virtually non-existent.	Involuntary servitude occurs when an adult is unable to quit a job s/he desires to leave – not by reason of economic necessity but rather by reason of employer's coercion. This includes labor camps but not work or service which forms part of normal civic obligations such as conscription or employment in command economies. This question does not ask you to assess the relative freedom of men and women from forced labor. Thus, a country in which both men and women suffer the same conditions of servitude might be coded a (0) for women, even though there is equality across the sexes.	4

v2clrelig	Is there freedom of religion? 0: Not respected by public authorities. Hardly any freedom of religion exists. Any kind of religious practice is outlawed or at least controlled by the government to the extent that religious leaders are appointed by and subjected to public authorities, who control the activities of religious communities in some detail. 1: Weakly respected by public authorities. Some elements of autonomous organised religious practices exist and are officially recognised. But significant religious communities are repressed, prohibited, or systematically disabled, voluntary conversions are restricted, and instances of discrimination or intimidation of individuals or groups due to their religion are common. 2: Somewhat respected by public authorities. Autonomous organised religious practices exist and are officially recognised. Yet, minor religious communities are repressed, prohibited, or systematically disabled, and/or instances of discrimination or intimidation of individuals or groups due to their religion occur occasionally. 3: Mostly respected by public authorities. There are minor restrictions on the freedom of religion, predominantly limited to a few isolated cases. Minority religions face denial of registration, hindrance of foreign missionaries from entering the country, restrictions against proselytising, or hindrance to access to or construction of places of worship. 4: Fully respected by public authorities. The population enjoys the right to practice any religious belief they choose. Religious groups may organise, select, and train personnel; solicit and receive contributions; publish; and engage in consultations without undue interference. If religious communities have to register, public authorities do not abuse the process to discriminate against a religion and do not constrain the right to worship before registration.	This indicator specifies the extent to which individuals and groups have the right to choose a religion, change their religion, and practice that religion in private or in public as well as to proselytise peacefully without being subject to restrictions by public authorities.	4
v2clfmove	Is there freedom of foreign travel and emigration? 0: Not respected by public authorities. Citizens are rarely allowed to emigrate or travel out of the country. Transgressors (or their families) are severely punished. People discredited by the public authorities are routinely exiled or prohibited from traveling. 1: Weakly respected by public authorities. The public authorities systematically restrict the right to travel, especially for political opponents or particular social groups. This can take the form of general restrictions on the duration of stays abroad or delays/refusals of visas. 2: Somewhat respected by the public authorities. The right to travel for leading political opponents or particular social groups is occasionally restricted but ordinary citizens only met minor restrictions. 3: Mostly respected by public authorities. Limitations on freedom of movement and residence are not directed at political opponents but minor restrictions exist. For example, exit visas may be required and citizens may be prohibited from traveling outside the country when accompanied by other members of their family. 4: Fully respected by the government. The freedom	This indicator specifies the extent to which citizens are able to travel freely to and from the country and to emigrate without being subject to restrictions by public authorities.	4

	of citizens to travel from and to the country, and to emigrate and repatriate, is not restricted by public authorities.		
v2cldmovem	Do men enjoy freedom of movement within the country? 0: Virtually no men enjoy full freedom of movement (e.g., North Korea). 1: Some men enjoy full freedom of movement, but most do not (e.g., Apartheid South Africa). 2: Most men enjoy some freedom of movement but a sizeable minority does not. Alternatively all men enjoy partial freedom of movement. 3: Most men enjoy full freedom of movement but a small minority does not. 4: Virtually all men enjoy full freedom of movement.	This indicator specifies the extent to which all men are able to move freely, in daytime and nighttime, in public thoroughfares, across regions within a country, and to establish permanent residency where they wish. Note that restrictions in movement might be imposed by the state and/or by informal norms and practices. Such restrictions sometimes fall on rural residents, on specific social groups, or on dissidents. This question does not ask you to assess the relative freedom of men and women. Thus, it is possible to assign the lowest possible score to a country even if men and women enjoy equal – and extremely low – freedom of movement. Do not consider restrictions in movement that are placed on ordinary (non-political) criminals. Do not consider restrictions in movement that result from crime or unrest.	4
v2cldmovew	Do women enjoy freedom of movement within the country? 0: Virtually no women enjoy full freedom of movement (e.g., North Korea or Afghanistan under the Taliban). 1: Some women enjoy full freedom of movement, but most do not (e.g., Apartheid South Africa). 2: Most women enjoy some freedom of movement but a sizeable minority does not. Alternatively all women enjoy partial freedom of movement. 3: Most women enjoy full freedom of movement but a small minority does not. 4: Virtually all women enjoy full freedom of movement.	This indicator specifies the extent to which all women are able to move freely, in daytime and nighttime, in public thoroughfares, across regions within a country, and to establish permanent residency where they wish. Note that restrictions in movement might be imposed by the state and/or by informal norms and practices. Such restrictions sometimes fall on rural residents, on specific social groups, or on dissidents. This question does not ask you to assess the relative freedom of men and women. Thus, it is possible to assign the lowest possible score to a country even if men and women enjoy equal – and extremely low – freedom of movement. Do not consider restrictions in movement that are placed on ordinary (non-political) criminals. Do not consider restrictions in movement that result from crime or unrest.	4

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