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To cite this article: Bjoern Soergel *et al* 2024 *Environ. Res. Lett.* **19** 124009

ENVIRONMENTAL RESEARCH
LETTERS

OPEN ACCESS

RECEIVED
28 February 2024

REVISED
16 September 2024

ACCEPTED FOR PUBLICATION
27 September 2024

PUBLISHED
30 October 2024

LETTER

Multiple pathways towards sustainable development goals and climate targets

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Keywords: sustainable development goals, climate change mitigation, green growth, post growth, integrated assessment models

Supplementary material for this article is available online

Abstract

The UN sustainable development goals (SDGs) and the Paris climate target require a holistic transformation towards human well-being within planetary boundaries. However, there are growing debates on how to best pursue these targets. Proposed transformation strategies include market- and technology-driven green-growth, shifting towards a sufficiency-oriented post-growth economy, and a transformation driven primarily by strong government action. Here we quantify three alternative sustainable development pathways (SDPs), Economy-driven Innovation, Resilient Communities, and Managing the Global Commons, that reflect these different societal strategies. We compare the quantifications from two integrated assessment models and two sectoral models of the buildings and materials sectors across a broad set of indicators for sustainable development and climate action. Our global multi-scenario and multi-model analysis shows that all three SDPs enable substantial progress towards the human development goals of the SDGs. They simultaneously limit global warming and prevent further environmental degradation, with the sufficiency-oriented Resilient Communities scenario showing the lowest peak warming and lowest reliance on carbon dioxide removal as well as the largest improvements in biodiversity intactness. The SDPs also alleviate the concerns about the biogeophysical and technological feasibility of narrowly-focused climate change mitigation scenarios. However, the shifts in energy and food consumption patterns assumed in the SDPs, ranging from moderate in Economy-driven Innovation to very ambitious in Resilient Communities, also lead to increased challenges regarding socio-cultural feasibility.

1. Introduction

Eight years after the landmark agreements on the UN sustainable development goals (SDGs) and the Paris climate target, it is becoming increasingly clear that continuing with current trends and policy ambition levels will fail to deliver on either of these. More than halfway through the 2015–2030 time horizon of the SDGs, progress towards the goals has been slow (Independent Group of Scientists appointed by the Secretary-General 2023, Malekpour *et al* 2023, UN Secretary-General 2023). For some SDGs, the COVID-19 pandemic and repercussions of armed conflicts such as the Russian invasion of Ukraine have led to a stalling or even reversal of the already slow progress (Naidoo and Fisher 2020). On the climate side, the window to reach the target of limiting warming to 1.5 °C is rapidly closing as emissions have surpassed their pre-pandemic level (United Nations Environment Programme 2023b). In light of this, there is an urgent need for more ambitious and integrated strategies to jointly pursue the SDG agenda and the Paris climate target (van Vuuren *et al* 2015, Bertram *et al* 2018, Iyer *et al* 2018, McCollum *et al* 2018, Fuso Nerini *et al* 2019, Moyer and Bohl 2019, Randers *et al* 2019, van Soest *et al* 2019, Fujimori *et al* 2020, Soergel *et al* 2021, Moallemi *et al* 2022, Riahi *et al* 2022, Moreno *et al* 2023, Hanna *et al* 2024, Orbons *et al* 2024).

Despite the broad consensus on these internationally agreed goals, there are fundamental debates on the strategies to implement them. These debates reflect different underlying paradigms on the roles of markets and technology, governments, or society as agents of change, as well as a different emphasis on economic growth, equity, and regionally vs. internationally oriented approaches. These different perspectives, as well as different regional priorities for sustainable development (SD), can be represented in scenario modelling through a set of multiple sustainable development pathway (SDP) scenarios (van Vuuren *et al* 2015, Aguiar *et al* 2020, Kriegler *et al* in preparation). Given the urgent need to accelerate the implementation of the SDGs and the Paris goals, it is important to identify measures that advance multiple targets simultaneously, and to do so robustly across different pathways. There is also a need for investigating potential trade-offs between different goals (e.g. economic growth vs biodiversity conservation, Otero *et al* 2020), and for quantifying to which extent different pathways can ameliorate or resolve such trade-offs.

To shed light on these questions, we present a multi-model analysis of new SDPs based on the scenario set developed in the SHAPE[18] project (Soergel *et al* 2024). The quantitative scenarios follow three SDP narratives, *Economy-driven Innovation* (EI), *Resilient Communities* (RC) and *Managing the Global Commons* (MC), that reflect the aforementioned paradigms as well as different strategies for the transformation of consumption and production across relevant sectors (Kriegler *et al* in preparation). Based on a set of socio-economic drivers, partially taken from shared socioeconomic pathway SSP1 (Riahi *et al* 2017) and partially derived specifically for the SDPs, and an extensive modelling protocol we quantify and compare SDG achievement and long-term SD prospects for each pathway. We highlight common features and differences in their underlying strategies and assess pathway-specific strengths, risks and barriers in a multi-dimensional feasibility analysis. Our multi-scenario and multi-model model approach represents two important advances: Assessing multiple pathways based on distinct paradigms provides insights on the achievability of SDGs and climate goals under different assumptions, and highlights which targets are particularly difficult to achieve. The use of multiple models with differing modelling approaches and system boundaries informs about the robustness by revealing areas of agreement as well as key uncertainties.

2. Methods

We develop the SDPs as ‘target-seeking’ scenarios designed to show different pathways towards a desirable future set by the targets of both the UN SDG Agenda and the Paris Agreement (Aguiar *et al* 2020). By exploring the space of such pathways, we quantify the magnitude of the transformations required to implement these targets. While we do not enforce achieving them by design, we generally construct scenario assumptions with the goal to enable rapid progress towards the SDGs. One notable exception is climate change mitigation (SDG 13), which is enforced through a carbon budget compatible with

[18] Sustainable development pathways achieving Human well-being while safeguarding the climate And Planet Earth”; https://shape-project.org.

the 1.5 °C target with small overshoot (supplementary material (SM) section 3.4). We then evaluate SDG achievement by comparing the model quantifications of the three different (but all very ambitious) SD strategies against a target space (Soergel *et al* 2021, van Vuuren *et al* 2022).

The quantitative SDP scenarios are based on narratives for SDPs that were co-developed by model analysts, social scientists and relevant societal actors (Kriegler *et al* in preparation). Each narrative provides an overarching vision on how best to pursue SD, resulting from a combination of specific SD strategies across a total of twelve relevant dimensions (summary of selected dimensions in table 1). This approach allows for substantial flexibility to build multiple different SDP narratives; here we focus on the three archetypal narratives: SDP-EI, SDP-RC, and SDP-MC. Broadly, SDP-EI relies on technology, markets and innovation as main drivers of transformation, with the state acting mainly as regulator to ensure that markets are competitive and outcomes are aligned with societal goals. It features a high-growth economic outlook and a supply-side-focused transformation based on price signals and well-regulated markets. By contrast, SDP-RC embraces sufficiency and wellbeing as central values, emphasising local community organisation with the state acting mainly as supporting partner. It pursues an equitable sharing of resources as part of an ambitious demand-side driven transformation and a post-growth economic outlook, especially in the Global North. Finally, SDP-MC relies on high-efficiency provisioning systems both on the supply and demand side, enabled by strong global and national institutions, with the state as key driving force of the transformation. Its economic outlook features an orientation towards human services, with moderate economic growth in the Global North and high economic growth in the Global South (Kriegler *et al* in preparation).

We quantify these scenarios using four models, the integrated assessment models (IAMs) REMIND-MAgPIE (Kriegler *et al* 2017, Dietrich *et al* 2019, Soergel *et al* 2021) and IMAGE (Stehfest *et al* 2014, van Vuuren *et al* 2017), the sector-specific model MESSAGEix-Buildings (Mastrucci *et al* 2021, Mastrucci and Ruijven 2023), and the industrial ecology model ODYM-RECC (Pauliuk *et al* 2021, Pauliuk 2023). The two IAMs give a 'full-system' perspective, while the latter two models provide deep-dives into the buildings sector and material flows (figure 1; see also SM for detailed model descriptions). While we do not fully couple the full-system IAMs with the sectoral models, a model comparison based on shared narratives and partially harmonised input assumptions (see below) represents a first step towards better including material stocks and flows in transformation scenarios.

We translate the qualitative SDP narrative elements to model settings via a structured modelling protocol (available as part of SM). Key inputs are harmonised quantitatively: Population and underlying demographics are taken from SSP1 (Lutz *et al* 2018) for all SDPs. For GDP and within-country inequality we use new quantitative scenarios that reflect the economic dimension of the SDP narratives and the normative goal to eradicate poverty (Min *et al* 2024) as scenario assumptions for our model quantification. Global and Global North/Global South GDP/capita values are shown in figure 2(a) below; a brief summary of the most important features of the GDP scenarios and regional GDP/capita values are given in SM section 3.2 and suppl. figure 5.

The demand for energy services, materials and food across the different scenarios is projected by the individual models. Modelling assumptions are guided by normative access targets from the SDGs, i.e. rapid reductions in hunger and improvements in water and energy access are assumed in the scenario design, for food and energy also taking into account the cost of the respective provisioning systems. We further use semi-quantitative specifications (e.g. high/medium/low) for each SDP scenario in the modelling protocol to enable qualitative harmonisation across models. For the sectoral models of the buildings sector and material flows the respective demand projections are already the main modelling result, whereas for the full-system IAMs they also serve as further quantified scenario drivers (see suppl. table S1).

In addition to the three SDP scenarios we quantify two further scenarios for comparison, both of them based on the middle-of-the-road SSP2 scenario (Riahi *et al* 2017). Our trends-continued reference scenario *SSP2-Ref* includes only current climate policies and no targeted SD policies, while SSP2-1.5C includes ambitious climate change mitigation but also no targeted SD policies. Importantly, our quantification of the three SDP and two reference scenarios only takes into account climate impacts from the current level of warming, but not future impacts from further warming.

3. Results

We compare the model quantifications across a broad array of indicators covering most of the 17 SDGs. Importantly, the indicators used for comparison can reflect scenario assumptions (e.g. GDP/capita), quantified scenario drivers (e.g. food and energy service demands), endogenous model results or post-processing indicators (see suppl. table S1 for an indicator overview and classification). Scenario assumptions and quantified drivers are summarised in

Table 1. Key features of the SDP narratives quantified in the models. The narrative summary in the first column is from Kriegler *et al* (in preparation); there also further details on the narratives can be found. The remaining three columns give a high-level summary of key aspects of the narratives with regard to the scenario modelling. The translation of the narratives into model parameterisations is provided in the modelling protocol (available as supplementary material).

Scenario title and narrative summary	Economic outlook	Energy & materials	Food & land
SDP-EI: Economy-driven Innovation towards sustainable development *In this world, liberal, functional, and global world views become prevalent. Societies embrace innovation, efficiency, global action and equal rights as key elements to depart from current unsustainable trends and drive the transition towards sustainable development. Competitive markets are seen as key drivers of innovation, opportunity and wealth. States act as regulators to align market outcomes with societal objectives. Peace prevails.*	- continued high economic growth in all regions, medium to strong convergence - reductions of inequality	- high demand for energy services, very high efficiency - medium to high material demand, high material efficiency	- sufficient calorie intake, modest reduction of food waste - modest increase in animal-free meat & milk alternatives - production efficiency optimised to enable land sparing
SDP-RC: Resilient Communities achieving sustainable development *In this world, an increasingly community-oriented world view is developed, emphasising solidarity and wellbeing. Societies emphasise regional diversity, transcend the capitalist economy model and rely on equitable sharing of resources and economic wealth to transition towards sustainable development. States act as partners to support community development and resource sharing. Peace prevails.*	- post-growth (convergence to stable GDP/cap) in Global North, continued economic growth in Global South, medium to strong convergence - very rapid reduction of inequality	- low demand for energy services through behavioural change, moderate efficiency - low material demand, medium material efficiency	- rapid transition to healthy calorie intake and nutrition - very low levels of food waste - changed diets reduce environmental footprint of agricultural system
SDP-MC: Managing the Global Commons to ensure sustainable development *In this world, global world views and the perception of global citizenship become prevalent. Societies support strong government-driven action to manage common and public goods. States and global institutions orchestrate the transition towards sustainable development, utilising markets, industrial and consumer policies, and investments in public goods. As part of the transition the focus on human services is increased and material consumption is de-emphasized. Peace prevails.*	- moderate economic growth in Global North, high growth in Global South, strong convergence - rapid reductions of inequality	- medium demand for energy services, high efficiency - medium material demand, high material efficiency	- gradual transition to healthy calorie intake and nutrition - low levels of food waste - combination of demand-side shifts and production efficiency reduces environmental footprint of agricultural system

figure 2. Endogenous and post-processing indicator results are shown in figure 3, followed by an SDG achievement index (figure 4). We also perform more in-depth analyses of the buildings and materials sectors (figure 5), climate change mitigation strategies (figure 6), and feasibility challenges (figure 7).

3.1. Economic development and material needs

The GDP scenarios of all three SDPs feature a near-complete convergence of income levels between Global North and Global South (see suppl. table S2 for regional mapping) over the course of the century (figure 2(a)). While in SDP-EI, and to a lesser extent in SDP-MC, per-capita income in the Global North

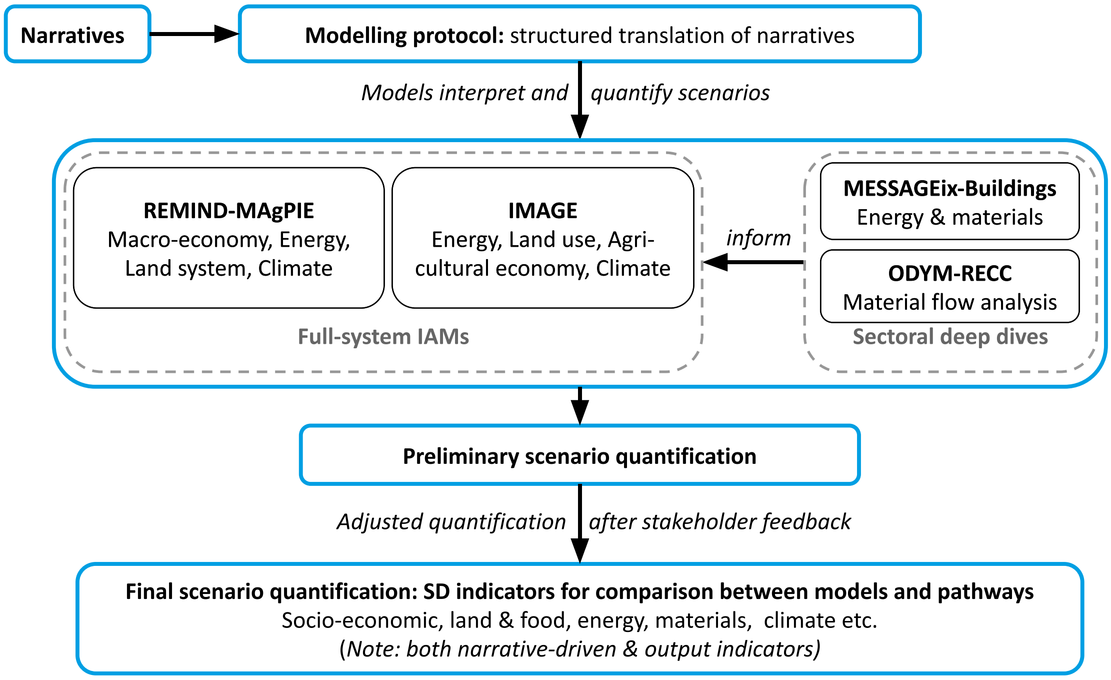

Figure 1. Setup of the SHAPE model comparison of sustainable development pathways. The scenario narratives were co-developed with stakeholders; and stakeholders provided feedback on initial preliminary scenario quantifications. Full-system IAMs and sectoral models are not coupled, but initial results from the sectoral models are used to guide the quantification of the respective sectors in the full-system models.

continues to grow, SDP-RC features a post-growth economic outlook with approximately constant per-capita income in high-income countries. Global GDP/capita spans a range of around 45 000 (SDP-RC) to nearly 100 000 $\$_{2010\ \mathrm{PPP}}$ (SDP-EI) in 2100, around 3–6 times the current (2020) value, with most of the growth occurring in the Global South. Within-country inequality as measured by the Gini coefficient reduces rapidly in all SDPs (fastest in SDP-RC, slightly slower in SDP-EI), leading to globally averaged values below 30 by 2050, comparable to the values in countries with the lowest income inequality today (Min *et al* 2024).

All SDP scenarios also assume a rapid reduction in the population at risk of hunger (SDG 2), with zero hunger being reached or nearly reached by 2050 (figure 2(b)). Reflecting the increased food demand in low-income countries, the global food demand projections for SDP-EI slightly exceed the trends-continued scenario (SSP2-Ref) until mid-century. They also feature only moderate reductions in the shares of animal-sourced food and in food waste in the Global North (Weindl *et al* in review). By contrast, SDP-MC and especially SDP-RC assume an ambitious demand-side transformation with a strong shift towards more plant-based nutrition (SDP-RC: over 90% of food demand by 2050) as well as a substantial reduction of food waste. In particular the Global North shifts away from the current consumption patterns with high shares of food with adverse health and/or environmental impacts and towards the diets recommended by the EAT-Lancet commission (Willett *et al* 2019), leading to a convergence in dietary patterns between Global North and Global South by 2050.

The SDPs also include rapid progress for several further access indicators from the SDGs (figure 2(c)), such as increased access to safe drinking water (SDG 6), a rapid reduction in the population relying on solid fuels for cooking, and near-universal electricity access (both SDG 7). The projections for energy service demands (figure 2(d)) reflect the underlying SDP narratives: SDP-EI and SDP-MC show only moderate breaks with historical trends, leading to a globally averaged passenger transport demand of 9,300–14 600 pkm/cap/yr and a floor space of 46–57 m^2/cap in 2050 (range across models and both SDP-EI and SDP-MC). By contrast, the SDP-RC scenario with its ambitious sufficiency orientation features a markedly lower passenger transport demand of 5,100–9,800 pkm/cap/yr and a floor space of 41–50 m^2/cap in 2050 (model range; see also suppl. figure S2 for model-specific results). Final energy (FE) consumption (also including industrial energy use; see also figure 5 below) is reduced moderately compared to today's level in SDP-EI (global average of 44–48 GJ/cap/yr in 2050), driven mostly by more efficient provisioning of energy services via electrification. SDP-MC (34–39 GJ/cap/yr) and SDP-RC (around 32–33 GJ/cap/yr) feature deeper reductions, driven by a combination of efficiency increases and demand-side shifts (SDP-MC), or a shift towards

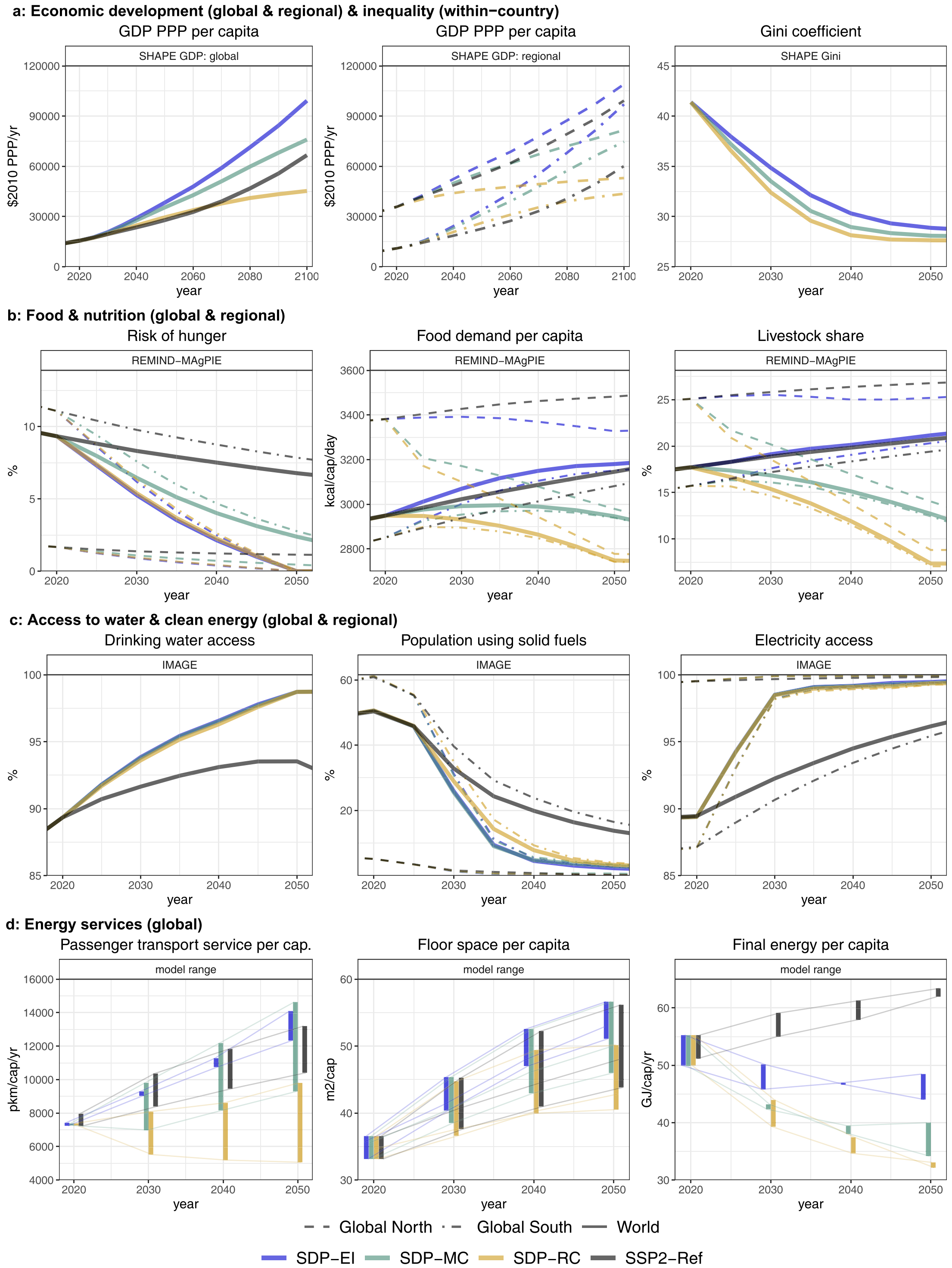

Figure 2. Overview of economic development, food & nutrition, water & energy access, and energy services in the SDPs. We also include a trends-continued scenario with only current climate policies (*SSP2-Ref*) for comparison. The economic development indicators (a) are used as harmonised input data across models. The two GDP/capita panels (global & regional) show values until 2100, all other panels focus on the period until 2050. For the food & nutrition indicators (b), we show only REMIND-MAgPIE data; the corresponding figure with IMAGE results is available as suppl. figure S1. The access indicators (c) are only available from the IMAGE model. For energy services (d), projections from multiple models are used: individual models are shown as thin lines (see also suppl. figure S2), while vertical bars display the range across models.

more sufficiency-oriented lifestyles especially in the Global North (SDP-RC).

3.2. SD outcomes

We show a number of SD outcome indicators in figure 3, covering the dimensions of poverty & inequality (SDGs 1 & 10), health (SDG 3), and food and land use (SDGs 2, 15). Our multi-model analysis robustly demonstrates that a continuation of current trends (*SSP2-Ref* scenario) is far off-track from meeting the SDGs. For example, we project only a modest reduction of extreme poverty until 2030

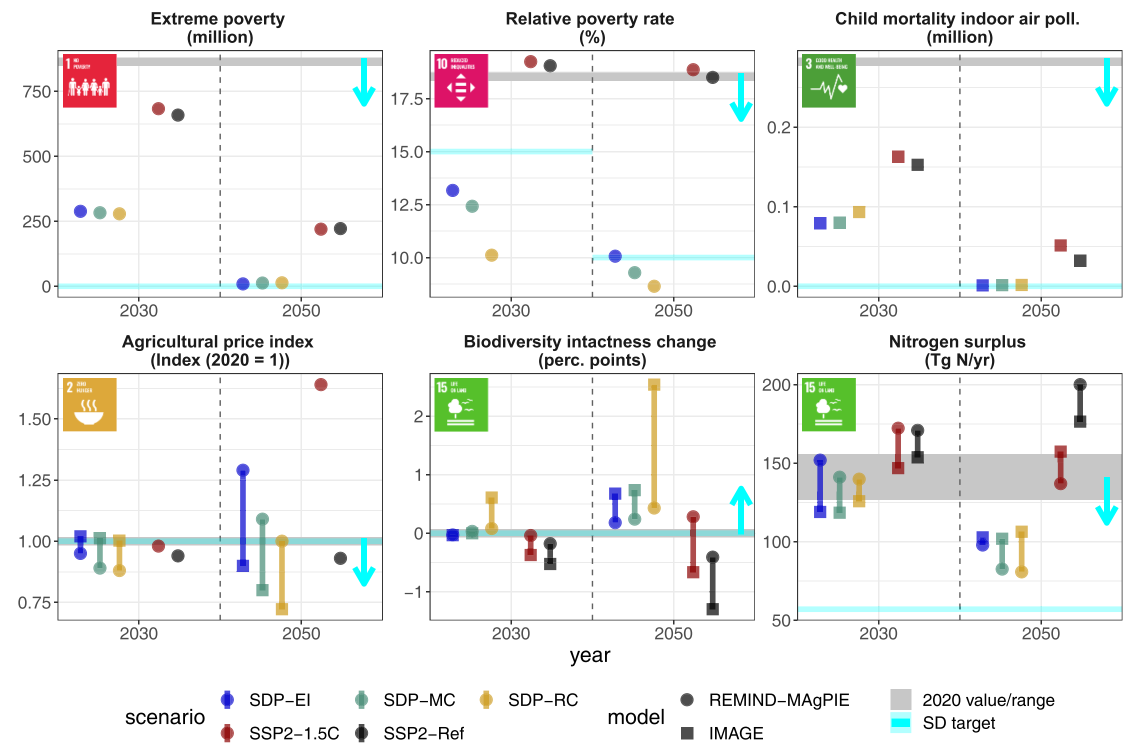

Figure 3. Comparison of selected sustainable development indicators: We compare across the three SDPs, and additionally to a climate-policy-only scenario (*SSP2-1.5C*) and a trends-continued reference scenario (*SSP2-Ref*). Symbols denote results from individual models; the model range is shown as a vertical line where data from multiple models is available (bottom row). Within each panel, results for 2030 (left) and 2050 (right) are shown. The shaded grey band represents 2020 values (model range for multi-model panels); the cyan line and arrow denote the 2030 (2050) target value (see suppl. table S1) and the direction of improvement. *Extreme poverty* refers to the international poverty line of 1.90 $\$_{\mathrm{PPP2011}}$/day, while *relative poverty* refers to an income below 50% of the median national income. For the panels *Agricultural price index* and *Biodiversity intactness change*, the targets are 'no increase compared to 2020' and 'no further degradation from 2020 value', respectively, therefore 2020 value and target line coincide. Absolute values for the *biodiversity intactness index* (BII) are currently around 80% (see supplementary table S1 for further information on interpretation of BII.).

(660 million people below the extreme poverty line of 1.90 $\$_{\mathrm{PPP2011}}$/day), and even by 2050 the goal of eradicating extreme poverty remains unmet (220 million). For a number of environmental indicators, such as the biodiversity intactness index (BII) or nitrogen pollution, we even project a worsening of the situation. In short, a trends-continued scenario will fail to deliver on both the social and environmental goals of the Agenda 2030.

Climate change mitigation without targeted SD policies (*SSP2-1.5C* scenario) can have synergistic effects for progress towards certain SDGs, e.g. preventing further worsening in BII. However, they also have adverse side effects, such as substantial increases in the prices for agricultural commodities, increased energy prices with negative consequences on access to clean cooking fuels and therefore indoor air pollution health effects, and small increases in poverty and inequality. This reinforces the findings of earlier single-model studies (e.g. Bertram *et al* 2018, Soergel *et al* 2021) that both a massive step-up in SDG implementation and a holistic strategy for integrating SD and climate change mitigation are needed.

The SDP scenarios substantially improve SD outcomes over the current-trends and climate-policy-only scenarios. For example, extreme poverty is reduced to around 280 million in 2030 and close to being fully eradicated by 2050. Furthermore, the trade-off of increasing agricultural prices due to climate policy is ameliorated or completely avoided in the SDP scenarios, as food-system emission reductions are achieved not only through price-driven measures but also facilitated through dietary change and efficiency improvements. Importantly, the enhanced levels of human development in the SDP scenarios do not come at the expense of further environmental degradation: we project moderate (SDP-EI & SDP-MC; SDP-RC from REMIND-MAgPIE) to substantial (SDP-RC from IMAGE) improvements in BII compared to today. Furthermore, the nitrogen surplus is halved by 2050 compared to the reference scenario (81–103 Tg N/yr across SDPs vs 176–200 Tg N/yr in *SSP2-Ref*). However, even in the scenarios with the strongest reductions (SDP-RC and SDP-MC from REMIND-MAgPIE) the boundary for nitrogen pollution remains transgressed.

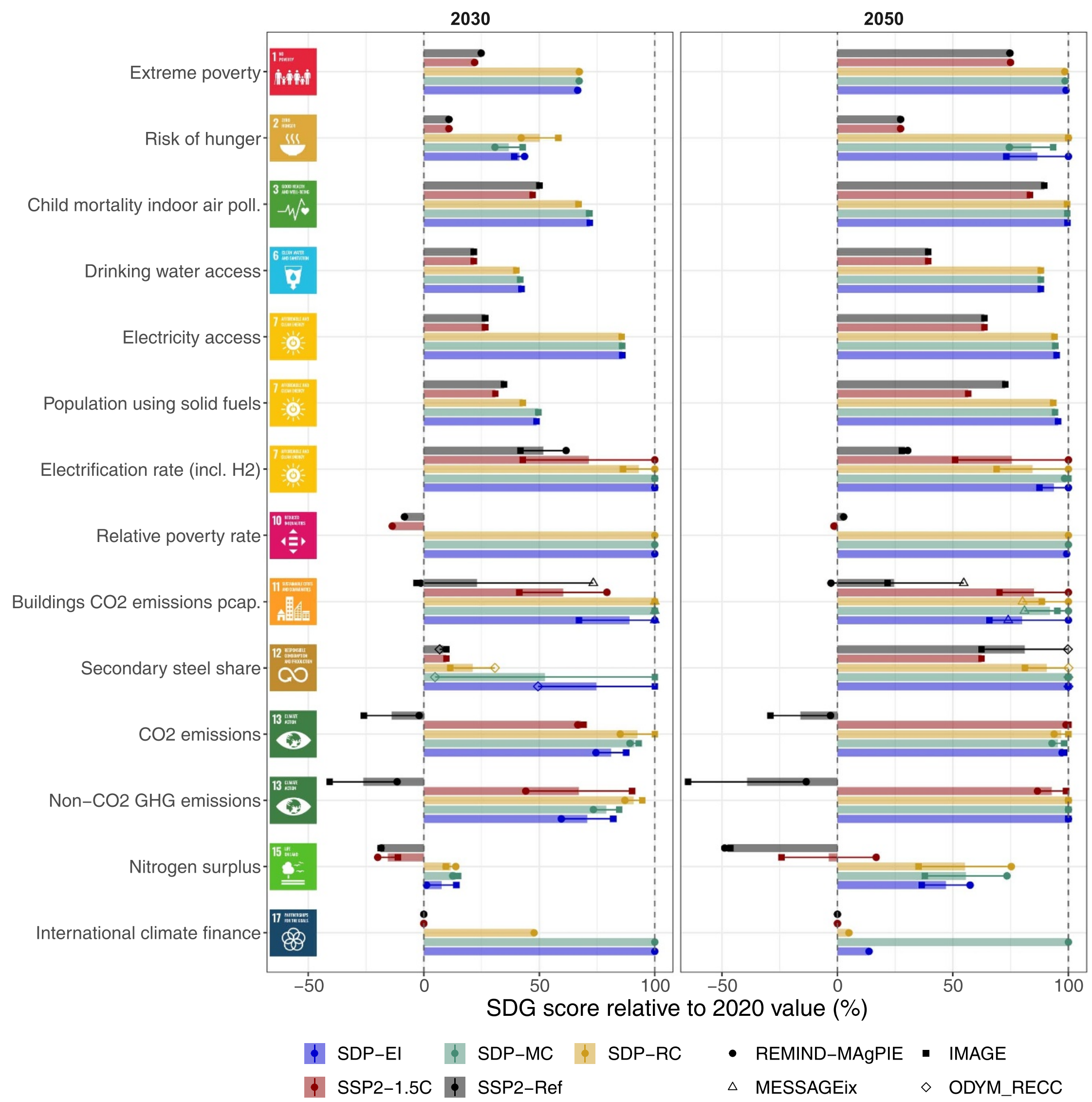

Figure 4. Index of SDG achievement across scenarios: We show a normalised SDG score that displays progress towards the target for 2030 (left panel) or 2050 (right panel) in the respective scenario (0% is the 2020 value, 100% means full achievement; see suppl. table S1 for targets). Individual model results and their range are shown by small symbols and the thin horizontal line, the average score across models is shown by the bar (individual results cut at 100% prior to averaging). The indicator selection combines the SD indicators from figure 3 (except for the already indexed indicators agricultural price index and biodiversity intactness) with access indicators relating to SDGs from figure 2, as well as selected material, climate and land/energy-transformation indicators from figures 5 and 6 below. For indicators associated with multiple SDGs (suppl. table S1), only the primary SDG is shown as an icon.

For a more aggregate perspective, figure 4 shows an SDG score that normalises indicator values to display progress towards the targets between 2020 and 2030 (2050) for all five analysed scenarios (integrating also indicators from figure 2 and the deep dives on buildings and materials and climate in figures 5 and 6 below). While the SDPs generally substantially accelerate progress towards the SDGs compared to the *SSP2-Ref* and *SSP2-1.5C* scenarios, many targets remain out of reach for 2030 due to the increasingly narrow time window. However, as already noted in earlier single-model studies (Soergel *et al* 2021, Moallemi *et al* 2022, Orbons *et al* 2024), a push for SDG implementation until 2030 and a continuation of SD policies afterwards can ensure that the targets are largely met at a later point in time. Comparing the three different SDP scenarios, we find that the overall level of SDG achievement in 2030 and 2050 is similar, with differences between the three alternative SDPs mostly being smaller than their common advantage over the SSP2-based comparison scenarios. Where differences exist, they reflect the differences in underlying SD strategies: For indicators with relatively close links to consumption patterns, such as reducing non-CO_2-emissions, SDP-RC makes the fastest progress. On the other hand, indicators related to the efficiency and/or circularity of production systems, such as secondary steel share, improve fastest in SDP-EI.

3.3. Buildings & energy-intensive materials

Already today the buildings and construction sector accounts for over a third of global greenhouse gas emissions, with a growing share from embodied emissions of construction materials. The goal to provide decent housing (SDG 11), together with increasing living standards in the Global South, can be expected to further accelerate this trend, resulting in an urgent need to reduce material demands, decarbonise their production, and shift to regenerative materials (United Nations Environment Programme 2023a). As a quantification of different strategies to enable decent housing but reduce emissions, here we project the demand for the energy- and emission-intensive materials iron & steel and cement in the buildings sector, accounting for scenario-specific trends in per-capita floor space (figure 2) and material efficiency and/or substitution strategies (see modelling protocol). While material demands in SDP-EI remain comparable to current levels until 2050 and SDP-MC achieves only moderate reductions, SDP-RC reduces iron & steel demand to 0.02–04 t/cap/yr and cement demand to 0.07–0.09 t/cap/yr in 2050 (figure 5, top row), enabled by both more intensive use of the existing building stock and shifting to wood-based construction.

In the SDP-MC and SDP-RC scenarios, also the total production of iron and steel and cement (all sectors) decreases considerably compared to the SSP2-based scenarios by 2050, alongside increases in the use of secondary (recycled) steel in all three SDPs (figure 5, bottom row). Reflecting a broader shift towards sustainable cities, direct CO_2 emissions from residential and commercial buildings are reduced rapidly in all SDPs, reaching values of around 0.1 t CO_2/cap/yr across models and scenarios by 2050.

3.4. Climate change mitigation strategies in the SDPs

In figure 6 we compare the mitigation strategies and the associated transformations of the energy and land-use systems between the SDPs, to our SSP2-1.5C scenario, and additionally to the IPCC AR6 ensemble of 1.5 °C scenarios (Byers *et al* 2022, Riahi *et al* 2022). All SDPs, and also SSP2-1.5C, limit the increase of global mean temperature (GMT) to slightly above 1.5 °C, with peak temperatures in the range of 1.56 °C–1.64 °C (median warming from AR6-calibrated climate assessment; Kikstra *et al* 2022). After the peak temperature is reached, warming is gradually reduced to well below 1.5 °C at the end of the century (EoC), making the scenarios

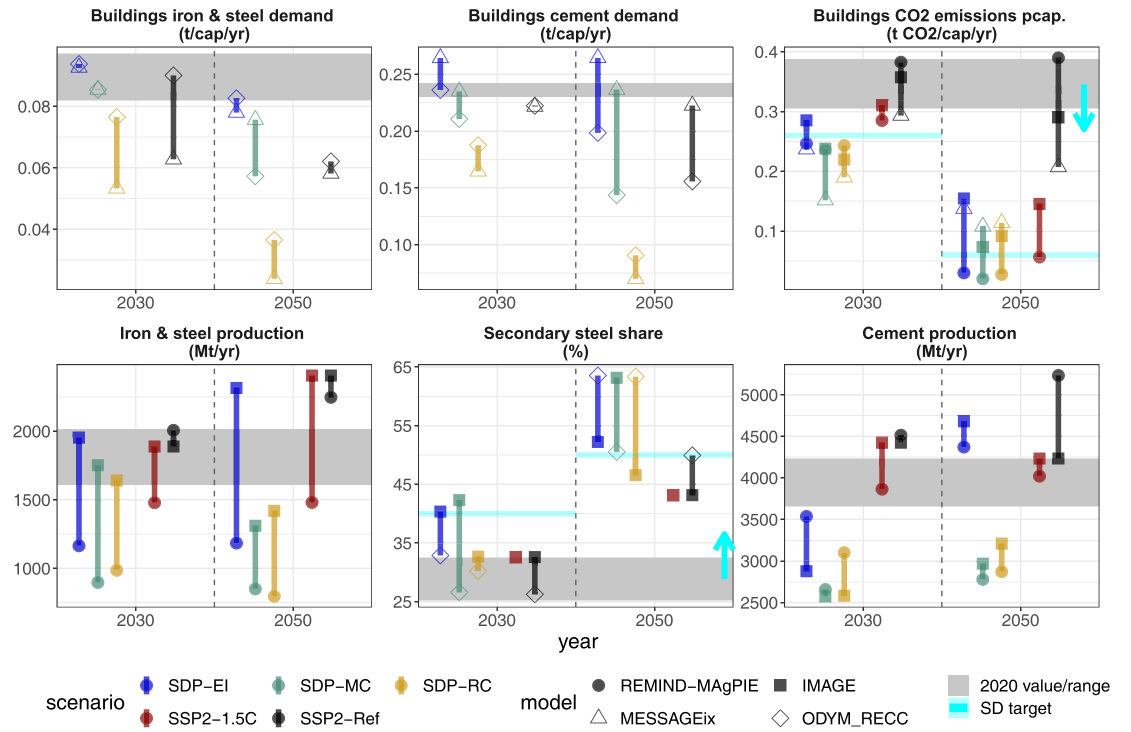

Figure 5. Buildings sector and energy-intensive materials: The top row shows indicators only for the buildings sector, while iron & steel and cement production (bottom row) include all sectors. Note that the representation of iron & steel and cement production in REMIND-MAgPIE includes a response to carbon pricing, while the IMAGE representation does not (see also suppl. table S1). The secondary steel share (bottom row, middle panel) from IMAGE is calculated across all sectors, while the values from ODYM-RECC are for buildings construction and passenger vehicles only. See the caption of figure 3 for a description of visual elements; here we additionally distinguish full-system IAMs (full symbols) and sectoral models (open symbols).

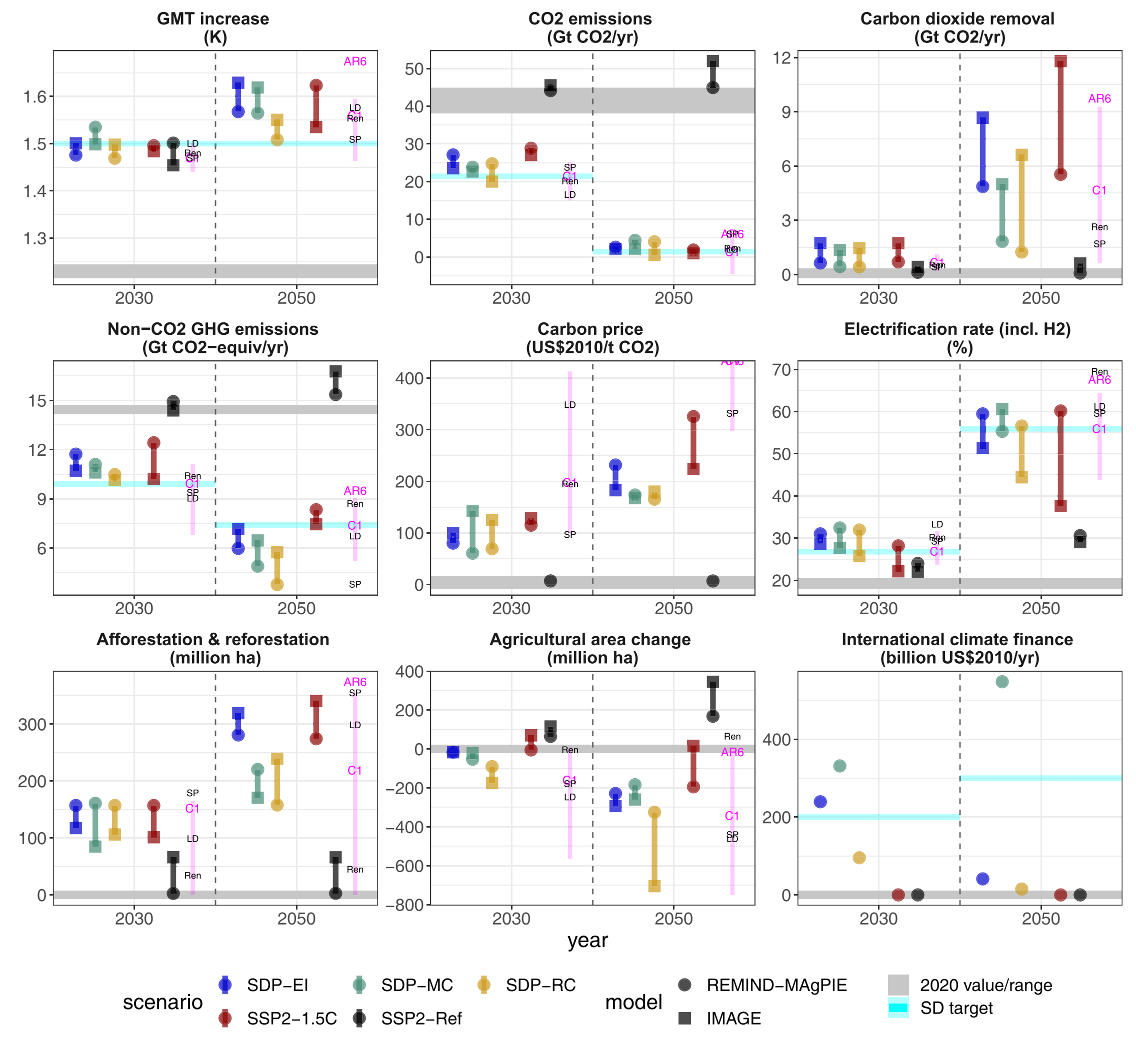

Figure 6. Climate change mitigation strategies across different SDPs: We compare a number of climate, energy and land indicators from the two full-system IAMs REMIND-MAgPIE and IMAGE. For each indicator panel, we show values for 2030 (left) and 2050 (right); values for 2100 are available in suppl. Figure 3. See the caption of figure 3 for a detailed description of visual elements. For additional comparison we show the 10%–90% range of 1.5 °C scenarios with no/low overshoot (C1) from the IPCC AR6 scenario DB in magenta. The 'C1' label marks the median of their range; the three illustrative mitigation pathways (IMP-SP, IMP-Ren, IMP-LD) are marked individually. In the panels *GMT increase* and *Carbon price* the vertical range is cut: the GMT increase of *SSP2-Ref* is 1.8 °C–2.1 °C in 2050, while the 90% range of AR6 C1 carbon prices in 2050 extends to above 1000 $/t CO_2. The panels *Afforestation & reforestation* and *Agricultural area* change show changes since 2020.

compatible with the long-term goal of the Paris Agreement to limit warming to below 1.5 °C (suppl. figures 3 and 4). SDP-RC has the lowest peak and EoC warming across the SDPs, indicating that combining the necessary decarbonisation of the supply side with deep demand-side shifts facilitates limiting warming both in the near and long term. In particular the shift towards healthier and more sustainable nutrition in SDP-RC (and to a lesser extent, SDP-MC) drives a rapid and deep reduction of non-CO_2 emissions to levels well below typical 1.5 °C scenarios, helping to limit the overshoot over 1.5 °C.

In SDP-RC and SDP-MC the need for carbon dioxide removal (CDR) is also considerably reduced compared to standard 1.5 °C scenarios: CDR in 2050 is reduced to around a quarter to half its value in SSP2-1.5C (range across models and both scenarios), demonstrating the potential of demand-side shifts to reduce the long-term reliance on CDR. SDP-EI, on the other hand, compensates for initially slower emission reductions with a higher degree of CDR, though still less than in SSP2-1.5C. However, the overall reliance on CDR remains a key uncertainty dimension in our model-scenario ensemble: REMIND-MAgPIE SDPs show consistently low CDR values (1.2–4.9 Gt CO_2/yr in 2050), at the lower end of the IPCC AR6 range of C1 (i.e. 1.5 °C with no/low overshoot) scenarios and below the typical range from the State of CDR report (25%–75% range of 7.6–11 Gt CO_2/yr; (Gidden *et al* 2024)). By contrast, the IMAGE SDPs show somewhat higher CDR deployment (5.0–8.7 Gt CO_2/yr) closer to the range of typical C1 scenarios.

The carbon price range required to meet the 1.5 °C target is broadly comparable between the three SDPs and across both models until mid-century (165–232 $\$_{2010}$/t$CO_2$ in 2050 for REMIND-MAgPIE;

167–183 $\$_{2010}/tCO_2$ for IMAGE), but lower than for a standard 1.5 °C scenario (SSP2-1.5C: 224–325 $\$/tCO_2$). While the demand-side shifts assumed in the SDP-RC and SDP-MC scenarios generally lower the mitigation challenge, the reduced availability of mitigation technologies (e.g. bioenergy, CCS) in SDP-RC increases the challenge on the supply side, resulting in broadly comparable carbon prices. However, in the long term (suppl. figure S3) the sufficiency-oriented SDP-RC scenario requires lower carbon prices (201–253 $\$/tCO_2$ in 2100) than SDP-MC (260–404 $\$/tCO_2$), and substantially lower prices than SDP-EI (410–569 $\$/tCO_2$) or SSP2-1.5C (606–665 $\$/tCO_2$). All SDPs further feature a rapid electrification of FE demand, with electrification rates (incl. indirect electrification via hydrogen) reaching values between 44%–57% (SDP-RC) and 55%–61% (SDP-MC) by 2050, comparable to (REMIND-MAgPIE) or higher (IMAGE) than in a standard 1.5 °C scenario.

On the land side, SDP-EI relies on improving production efficiency, and also features the highest afforestation and reforestation across the SDPs (281–319 Mha by 2050), largely with fast-growing plantations to increase land carbon sequestration (for details see Weindl *et al*). By contrast, SDP-RC relies on a strong dietary shift towards a healthy and environmentally friendly nutrition. This reduces the land area required for the agricultural system (cropland & pasture) by 325–705 million ha by 2050, freeing up land for natural regrowth of native tree species and thereby enabling higher gains in biodiversity intactness in SDP-RC than in SDP-EI (figure 3).

The SDP scenarios also include stylized schemes for international climate finance, assuming an international redistribution of part of the carbon pricing revenues (Soergel *et al* 2021; see modelling protocol for details). The internationally oriented SDP-MC scenario reaches around 330 billion $\$_{2010}$/yr of international climate finance by 2030 and nearly 550 billion $\$_{2010}$/yr by 2050, more than compensating for the near-term costs of climate policy in developing regions of the Global South (Africa, South Asia). By contrast, SDP-RC has the lowest level of international financing, with 96 billion $\$_{2010}$/yr in 2030 only at the level of the 2009 Copenhagen pledge, reflecting its regionally oriented narrative.

3.5. Pathway-specific feasibility risks

Our SDP scenarios show that in principle large progress towards the SDGs and the Paris climate target is possible. However, they also show that such progress would require a rapid and deep departure from historical development patterns, and as such the SDP scenarios also highlight the magnitude of the required transformations. For the underlying socio-economic scenarios we take primarily a normative approach, with the SDP scenarios reflecting different socio-economic futures broadly aligned with the goals of eradicating poverty and reducing inequality. On the other hand, we can assess the feasibility of the associated energy and food/land system transformations by comparing our scenarios to estimates of biogeophysical limits as well as constraints set by the current techno-economic and socio-cultural context (Brutschin *et al* 2021, Riahi *et al* 2022). Low feasibility concerns indicate a transformation broadly in line with historical examples, while high levels point towards a change without historical precedence (for details on method, indicator choice and threshold see SM section 3.6).

As elements of *biogeophysical* and *technological feasibility*, we consider the reliance on primary energy sourced from biomass (biogeophysical) and the scale-up of carbon capture and storage (technological). All three SDPs show substantial reductions in feasibility risks along both dimensions compared to a standard 1.5 °C mitigation scenario (SSP2-1.5C), and also compared to the range (10%–90%) of AR6 C1 scenarios (figures 7(a) and (b)). The reductions in feasibility risks are stronger in SDP-MC and especially in SDP-RC thanks to its ambitious demand-side shifts, and more moderate in SDP-EI.

Concerning *economic feasibility* we assess the cost of climate policy in terms of a reduction of the GDP growth rate (compared to a reference scenario without climate policy) as a high-level indicator (figure 7(c)). In SDP-MC and SDP-RC the growth rate losses and associated feasibility concerns are substantially reduced compared to SSP2-1.5C, both for the Global South and the Global North (mainly 2030–2040 decade). A more regionally disaggregated perspective reveals short-term policy gains for Africa (all SDPs) and South Asia (SDP-MC) thanks to international climate finance, but also near-term policy costs for both Middle East and the former Soviet Union countries in SDP-EI. We also assess changes in electricity prices because of the crucial role of electrification for the energy transition (figure 7(d)). Given the need for compensating mechanisms in the case of high price increases, this indicator additionally also touches upon aspects of *institutional feasibility*. We find that there is an initial scarcity of renewable electricity due to high initial investment requirements, which is reflected in substantial increases in electricity prices in all three SDPs until 2030, comparable to (Global North) or slightly higher (Global South) than in SSP2-1.5C. However, the associated feasibility risks only affect a transition period, as electricity prices reduce to around their 2020 levels after 2030.

As all SDPs rely on changes in energy, material and food demand to a certain extent (SDP-RC most strongly, SDP-EI the least), the *socio-cultural feasibility* dimension is of particular importance. Here we focus on the share of calories from livestock products and the use of FE per capita as high-level proxies, and quantify feasibility challenges in terms of rates of change over decadal periods (figures 7(e) and (f)).

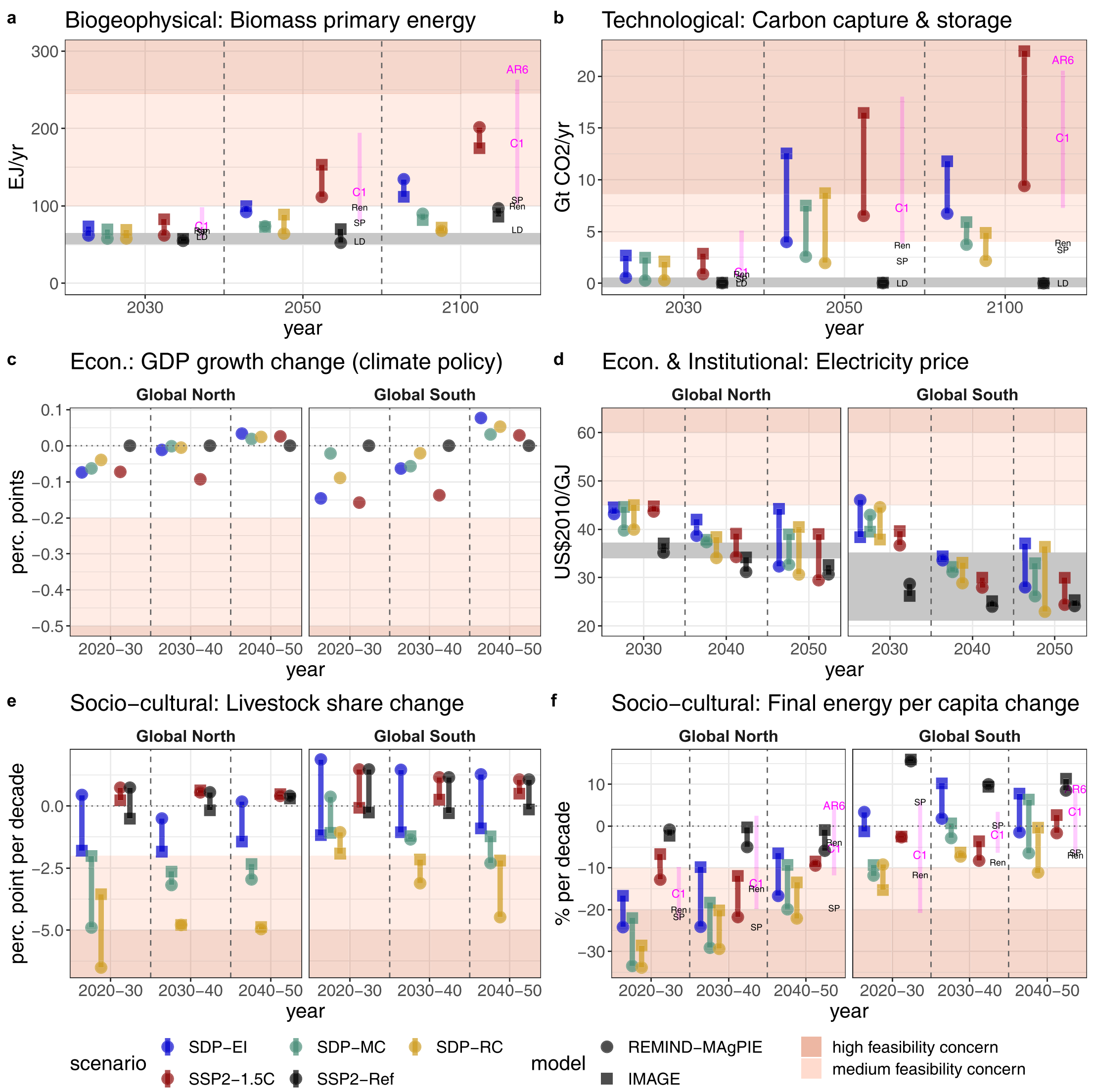

Figure 7. Feasibility analysis: We quantify feasibility concerns for a set of feasibility dimensions and indicators. Model results from this study, 2020 values (grey bands) and ranges from the AR6 scenario DB (magenta) are drawn as in figures 3, 5 and 6. Light and darker orange shadings mark indicative thresholds for medium and high feasibility concerns drawn from the literature and/or historical data (see SM for details on indicator selection and thresholds). Panels (a) and (b) compare values for 2030, 2050 and 2100 against the corresponding global thresholds. Panel (c) shows the difference in annual regional GDP growth rates between a climate policy and a reference scenario (REMIND-MAgPIE model only) averaged over 10-year periods, while panel (d) shows regional electricity prices. Panels (e) and (f) compare regional changes in livestock share and final energy per capita over decadal periods against thresholds for rates of change.

The rapid reductions in livestock share assumed in SDP-MC and especially SDP-RC lead to substantially increased feasibility concerns in the Global North, and in SDP-RC also in the Global South from 2030 onwards. Similarly, the ambitious FE demand reductions assumed in the Global North lead to increased feasibility concerns, especially for SDP-MC and SDP-RC in the next two decades. Feasibility concerns remain mostly moderate for the Global South, as the SDP scenarios aim for sufficient energy for decent living standards (Kikstra *et al* 2021), which can even lead to increasing FE values. As an exception, there are initial reductions of FE per capita around or above 10% in the initial 2020–2030 decade of SDP-RC and SDP-MC. However, these are mostly related to the phase-out of traditional biomass with its poor relation between FE use and provided energy service (Baltruszewicz *et al* 2021). This points to changes in FE being an imperfect proxy of feasibility, and future refinements of the framework should work towards separating changes in energy service demands and efficiency.

Relatively low absolute values of FE/capita in some Global South regions in SDP-RC could nonetheless indicate a remaining challenge with providing sufficient energy for positive human development outcomes. However, the SDP scenarios also assume ambitious reductions in income inequality (strongest in SDP-RC, figure 2(a)), which also imply strong reductions in energy inequality. Together with energy efficiency improvements, this largely ensures sufficient provision for a development towards decent living standards despite low average energy use (Kikstra *et al* in review).

4. Discussion and conclusion

The scenario set presented in this study represents a number of important advances. As target-seeking scenarios encompassing the broader SD space, the SDPs substantially broaden the focus beyond climate change mitigation. We show that holistic SDPs can accelerate progress towards the human development goals of the Agenda 2030, while simultaneously limiting global warming in line with the Paris Agreement and preventing further environmental degradation. Furthermore, the SDPs also soften or resolve many of the trade-offs of narrowly focused climate-only-pathways, for example concerning the effects of climate change mitigation on agricultural prices. In addition, the SDPs also alleviate the concerns about geophysical and technological feasibility of standard 1.5 °C mitigation scenarios. Importantly, our multi-model assessment of these pathways also enables a more robust assessment of such feasibility concerns and key synergies and trade-offs, shedding light on robust strategies but also on key uncertainties.

By quantifying three distinct alternative paradigms on how to pursue SD, our set of SDP scenarios enables a broader assessment of the policy option space. In particular the SDP-RC scenario fills an important gap in the current scenario literature by quantifying a post-growth SD scenario (Otero *et al* 2020, Hickel *et al* 2021, Moyer 2023). We show that substantial progress towards SD within planetary boundaries is possible in all three SDPs, despite their substantial differences in underlying societal and economic paradigms. The ambitious demand-side shifts assumed in SDP-RC limit the overshoot over 1.5 °C most effectively, reduce the long-term reliance on CDR, and lead to the best environmental outcomes in terms of biodiversity intactness across the SDPs. On the other hand, these ambitious demand side shifts lead to concerns about socio-cultural feasibility, at least when evaluated within the current socio-political context.

A number of limitations to our analysis remain: First of all, we use a range of optimistic socio-economic scenarios for population, GDP and inequality as a basis for quantifying the SDPs, representing substantial breaks with historically observed development patterns by design. These scenario assumptions reflect the three different (but all very optimistic) underlying SDP narratives, and as such realising any of these scenarios is contingent on the fundamental shifts in values, governance and economic system envisioned by its narrative. Furthermore, it would also have strong requirements on institutional quality and peace (SDG 16), which are often considered key enablers or even preconditions for SD (Soergel *et al* 2021, Leininger *et al* in preparation). However, as our modelling does not cover such links between socio-economic and institutional development, we cannot assess the feasibility of our socio-economic scenario assumptions.

Our model ensemble further does not allow for endogenous quantification of education (SDG 4) and gender equality (SDG 5). While these goals are reflected implicitly by the use of SSP1 demographic data that assumes optimistic trends in education and gender equality (Kc and Lutz 2017), we do not estimate investment needs for these SDGs. Similarly, we do not quantify the investment needs associated with near-universal drinking water access (for cost estimates of different SDG-related infrastructure see Rothman *et al* 2015, Kulkarni *et al* 2022). Life below water (SDG 14) is also not covered in our indicator set, but given the close links between cumulative CO_2 emissions and ocean acidification (Hofmann *et al* 2019) it is also covered indirectly.

While key scenario drivers such as energy, material and food demand are based on more detailed sectoral modelling and empirical work (Levesque *et al* 2019, Bodirsky *et al* 2020, Mastrucci *et al* 2021, Pauliuk *et al* 2021, Pehl *et al* 2023), these models do not explain the underlying policy mixes and socio-cultural dynamics that would bring about such rapid and deep demand-side shifts (see also Dombrowsky *et al* accepted), and also the potential consumer utility losses of such demand-side shifts are not quantified. Furthermore, the degree of decoupling between GDP and energy demands in our scenarios remains mostly driven by scenario assumptions. Future scenario research should aim to resolve the underlying dynamics more endogenously, for example by modifying the utility function (Li *et al* 2023, Kikstra *et al* 2024).

Our modelling setup also does not take into account adverse impacts of climate change beyond the current levels of warming on SDG achievement. Therefore, our results include only direct co-benefits of mitigation policies, but not the indirect benefits to the SDG agenda of avoiding the adverse impacts of climate change that would occur in the absence of ambitious mitigation policies (Byers *et al* 2018, Birkmann *et al* 2022).

Despite these limitations and the associated needs for future research, our set of SDP scenarios represents a possible focal point for future SDG pathway analysis. Our results reinforce the message that SDG implementation needs to be sped up drastically in the second half of their 2015–2030 time horizon. At the same time, our analysis of different possible longer-term SD pathways broadens the policy option space and can inform the debate on post-2030 SDGs and strategies.

Data availability statement

The scenario data that support the findings of this study can be explored interactively at the following URL: https://shape.apps.ece.iiasa.ac.at/. They are also available for download at https://doi.org/10.5281/zenodo.13752116.

Acknowledgments

The authors thank Elina Brutschin for support with an update of the feasibility concern threshold for dietary changes. B S further thanks the macroeconomic modelling group at PIK, in particular Marian Leimbach, Nico Bauer and Franziska Piontek, for helpful discussions, and Dominika Soergel for feedback on visualisations and proofreading of the manuscript. This work has been partially funded through the project SHAPE. SHAPE is part of AXIS, an ERA-NET initiated by JPI Climate, and funded by FORMAS (SE), FFG/BMWFW (AT), DLR/BMBF (DE, Grant No. 01LS1907A), NWO (NL) and RCN (NO) with co-funding by the European Union (Grant No. 776608). This work was also supported by the European Union's Horizon 2020 research and innovation programme under Grant Agreement Nos. 821124 (NAVIGATE) and 821471 (ENGAGE), and by the European Research Council (ERC) under the H2020-EU.1.1. Excellent Science Programme under Grant No. 819566 (PICASSO). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. The SDG icons used in the figures and tables were created by the United Nations.

Author contributions

B S conceived the multi-model analysis and led the writing of the manuscript, with inputs from S R, V D, I W, A M, F C, J K and E K. B S, S R, V D, I W, A M, F C, G A and A B performed the scenario model runs with the four participating models; JK contributed the climate assessment. All other authors contributed to scenario design including the co-design with stakeholders, the development and scenario implementation of individual models, or the writing of the manuscript.

Code availability

The code to perform the multi-model analysis is available from the corresponding author on reasonable request. Information about open-source access to the source code of individual models can be found in the respective model descriptions (see Supplementary Material).

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