Global Sustainability

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A review of existing model-based scenarios achieving SDGs: progress and challenges

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Review Article

Cite this article: Orbons K, van Vuuren DP, Ambrosio G, Kulkarni S, Weber E, Zapata V, Daioglou V, Hof AF, Zimm C (2024). A review of existing model-based scenarios achieving SDGs: progress and challenges. *Global Sustainability* **7**, e3, 1–7. https://doi.org/10.1017/sus.2023.20

Received: 10 May 2022
Revised: 19 August 2023
Accepted: 14 September 2023

Keywords:
adaptation and mitigation; earth systems (land; water; and atmospheric); food security; modelling and simulation; policies; politics and governance

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Abstract

Non-Technical Summary. In 2015, the United Nations articulated the ambition to move toward a prosperous, socially inclusive, and environmentally sustainable future for all by adopting the Sustainable Development Goals (SDGs). However, little is known about the pathways that could lead to their concurrent achievement. We provide an overview of the current literature on quantitative pathways toward the SDGs, indicate the commonly used methods and indicators, and identify the most comprehensive pathways that have been published to date. Our results indicate that there is a need for more scenarios toward the full set of SDGs, using a wider range of underlying narratives.

Technical Summary. Quantitative goal-seeking scenario studies could help to explore the needed systems' transformations to implement the 2030 Agenda for Sustainable Development by identifying enabling conditions and accounting for the synergies and trade-offs between the SDGs. Given that the SDGs were adopted some time ago, here, we review the existing global scenario literature to determine what it can offer in this context. We found only a few scenarios that address a large set of SDGs, while many more deal with specific clusters of 2–6 SDGs. We identified the most frequent clusters and compared the results of the most comprehensive sustainable development scenarios. The latter is complicated because of the diversity of methods, indicators, and assumptions used. Therefore, we suggest that an effort is needed to develop a wider set of scenarios that would achieve multiple SDGs, using a more standardized framework of targets and indicators.

Social Media Summary. This study reviews the current global pathways toward the SDGs and shows the need for a broader set of SDG scenarios.

1. Introduction

In order to support the 2030 Agenda for Sustainable Development (United Nations, 2015), 17 Sustainable Development Goals (SDGs), supported by 169 sub-targets, were agreed upon by the international community. These goals and targets express the ambition to lift the global population out of poverty, protect the earth's ecosystems, and ensure prosperity for all. However, the adoption of these goals exposed a critical gap in the knowledge on how to achieve them. This is far from trivial, as most goals require a substantial collective effort over multiple years, while important linkages exist between the goals (Nerini et al., 2017; Pradhan et al., 2017; van Soest et al., 2019). Filling this knowledge gap is urgent given the slow progress, which was further exacerbated by the COVID-19 pandemic (Allen et al., 2017; United Nations, 2021). Model-based scenario analysis could help explore possible routes toward achieving the SDGs and identify the required actions (Allen et al., 2016; Sachs et al., 2019; United Nations, 2019). Such scenarios have successfully supported climate and biodiversity policy-making, largely via comprehensive literature assessments as conducted by the Intergovernmental Panel on Climate Change and Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Using similar model-based scenarios for supporting the SDGs is not straightforward. New methods will be required, as most models often only cover a sub-set of SDGs and the synergies and trade-offs between them (van Soest et al., 2019). Given the nature and complexity of several goals, transdisciplinary efforts consisting of numerical models and social science insights are needed.

Over the past years, important scientific progress has been made in developing scenarios toward the SDGs, including the expanding body of literature that addresses the possible synergies and trade-offs between them (Nerini et al., 2017; Pradhan et al., 2017; van Soest et al., 2019). In this context, we conducted a review to determine whether the current literature can already identify quantitative pathways toward several SDGs at the global scale. This review identifies the strengths and weaknesses of existing pathways and related methods

and may serve as a stepping stone for further progress. We identified 140 papers that are global in scope and quantitatively explore pathways toward one or multiple SDGs by 2030 or beyond (see Supplementary Information for the methods and full list). For each of these papers, we indicated the SDGs covered, the type of model used, and the type of scenarios explored. Many papers do not address the SDGs directly but de facto explore similar goals – often based on related international agreements (e.g. the Paris Agreement). Some goals are represented almost entirely through one of their sub-targets. Examples are SDGs 3 and 11 (air pollution) and SDG12 (food waste).

2. Methods

2.1 Creating the database of relevant papers

The database of the papers forms the center of our analysis. Papers were included if they: (1) contain quantitative projections to 2030 or beyond; (2) aim to achieve at least two SDGs or similar goals; and (3) are relevant to the global scale. Relevance was determined on a case-by-case basis, based on scope and scalability. Studies looking only at the implications of current trends were not included, even when the situation is projected to improve for certain goals under a business-as-usual situation. Regarding the rule on multiple SDGs, some exceptions were made in order to cover a wider range of SDGS.

The selection was done based on a literature research and a request to submit relevant papers sent out via the IAMC mailing list (Integrated Assessment Modelling Consortium, that is, a network organization of integrated assessment modelling teams).

2.2 Literature research and survey to global teams

The following steps were taken:

- First, 12,531 articles in the final stage of publication were retrieved from the Scopus database, using the following search string to search the title, abstract, and keywords: ('sustainable development' OR SDG) AND (pathway OR scenario OR synergy OR 'trade-offs' OR 'Integrated assessment' OR projection OR interlinkage OR 'future prospect').
- Next, five particularly relevant and five irrelevant papers were selected from a cursory overview of the results. These were used as starting points to rank the query's output according to relevance to the set criteria through an iterative process using the machine learning tool ASReview (van de Schoot et al., 2021). For every iteration, the reviewing tool suggested the next most relevant paper that a reviewer indicated as relevant or irrelevant. After 60 of these iterations, the ranked database was retrieved.
- The 1,500 highest ranked papers were screened, on abstract, independently by two reviewers. After the resolution of the inter-annotator disagreement, 117 papers were categorized as relevant.

This search was complemented by a request for papers exploring pathways toward the SDGs from global modelling teams, producing 133 papers. Of these, 23 met the criteria and were not yet found in the previous steps (see Supplementary Information for an overview of all records included and the selection).

2.3 Database

The final database of 140 papers (included as Supplementary Information) consists of the combination of both results.

- Subsequently, we documented the models and methods used, timescale, scenarios, and SDGs covered for each paper in the database.
- An SDG was attributed to a paper if it quantified progress on a variable directly related to the goal. If co-benefits were not made explicit, then the SDG was not included. For instance, although reducing GHG emissions positively impacts ocean eutrophication, climate mitigation studies do not automatically tick the SDG14 box unless this co-benefit was made explicit in the paper.
- We also only included papers that explicitly discuss specific parameters. As many papers are using the SSP1 scenario, one could implicitly attribute the narrative of SSP1 to these papers. However, in this review, we only assigned scenarios to SDGs when these were explicitly and, preferably, quantitatively addressed.
- We did not document whether the SDGs were achieved or not. The main reason for this is the lack of consensus on what it means to reach a goal or target and the difficulty of differentiating between specific sub-targets of the goals and a goal in its entirety. The issue would thus become overly complex and error prone. Especially because many of the papers in the database are not target-based but make ex-ante evaluations of certain scenario assumptions.
- Market basket analysis of the final database revealed the common clusters of SDGs in the literature.

Although we have attempted to establish a representative database of the current literature on quantitative pathways toward the SDGs, certain biases in the data are inevitable. In part, this can be attributed to the inclusion criteria. For instance, because the papers needed to be relevant to the global scale, some SDGs were more likely to be included than others. For example, climate change is inherently a global affair, while access to water often requires region-specific solutions that are difficult to include in a quantified global model. Moreover, as pointed out by Moyer and Bohl (2019), some SDGs seem to be achieved on the global scale, while many, mostly developing, countries fail to meet the targets. Finally, our decision to only include modelling studies with quantitative future projections provided a higher chance of finding more quantifiable SDGs (related to earth sciences, demographics, economics or engineering) as opposed to some more social development SDGs. However, as our survey to model teams, in the end, did not lead to further new papers, we believe that the database is representative of relevant studies published in the scientific literature.

2.4 Selection of exemplary papers

For further analysis, six exemplary papers for comprehensive sustainability pathways were selected from the established database. For comparison, this selection was complemented with the study by Randers et al. that only includes a business-as-usual scenario but measures the progress for all 17 SDGs. The other studies stood out because of their breadth. All covered targets connected to at least seven different SDGs mostly using multiple indicators per goal and making significant progress toward

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achieving them. Some papers still covering multiple SDGs were not included based on their limited scope (mostly because SDGs results were reported as co-benefits of a specific measure, typically related to energy or diets).

2.5 Description of used indicators

Five of the seven studies explicitly relate their results to the SDG targets and indicators. Apart from the Randers study, all of them include multiple scenarios, typically a reference scenario against which the results of multiple other pathways are compared. Here, we document the results of the reference scenarios and the most sustainable pathway for each paper as reported in the study itself. This is done for every indicator related to an SDG; see Table S1. Grubler et al. (2018) merely indicate if progress is made toward an SDG, but not whether specific targets are being met, so we attempted to estimate the progress toward the goal. The progress and indicators in the two Van Vuuren papers (2015, 2017) were documented by their author. Their results were compared to the targets used in the other selected studies and the target space to quantify the progress.

2.6 Assessment of the content of selected studies

The cells are colored red in the case of deterioration, that is, moving away from the target, orange in the case of stagnation (~0–25% progress), yellow indicates moderate progress (~25–65%), light green stands for significant progress (~65–99% progress), and finally, a cell is colored dark green when the goal is expected to be achieved in the scenario (Table 1). The average progress per SDG for each study's reference and most sustainable scenario is shown in Table 1. Different indicators related to the same goal show different results in many cases. In those cases, an estimate of the average progress was made. When the results diverged too greatly, for example, if some targets were projected to be achieved while other indicators showed deterioration, the cell was colored grey. As the selected studies use different targets and indicators, the significance of the comparison is limited. The indicators used per SDG differ between papers. Sometimes, two distinct indicators of the same goal hold near-identical information, such as radiative forcing levels *vs* the mean temperature increase. In contrast, others are rather different, for instance, because they represent different sub-targets. The sheer number of indicators, 92 in total, shows the diversity and the difficulty of directly comparing the progress along those lines between the various studies.

3. Results and discussion

The database reveals valuable information regarding the current state of the art in sustainable development scenario literature. We identified 30 articles that address more than 5 SDGs, of which only one uses indicators related to all 17 SDGs (Soergel et al., 2021b). The scenarios are typically based on a combination of the Shared Socio-economic Pathways (SSPs) (O'neill et al., 2014) or a reference scenario combined with various policy scenarios. Many papers include a scenario based on SSP1 ($N = 43$), whose narrative is most closely aligned with sustainable development amongst the SSPs. As the storyline of the SSP1 scenario addresses many SDG topics (Zimm et al., 2018), covering issues related to gender equality, education, and health that are also relevant to demographic development, one could implicitly attribute these to the underlying papers. However, in this review, we only assigned scenarios to SDGs when these were explicitly addressed.

SDG13 (climate action) is the most addressed goal ($N = 107$), followed by SDG2 (zero hunger) ($N = 59$), SDG7 (affordable and clean energy) ($N = 58$), and SDG15 (life on land) ($N = 54$) (Figure 1). SDG13 and SDG7 are the most frequently co-occurring goals ($N = 49$), with the former being, in fact, the most common co-occurring goal of all SDGs (Figure 1). For instance, 81% of the papers looking at SDG3 (good health and well-being) and all that study SDG11 (sustainable cities) also include climate policy. The centrality of SDG13 can be explained by the importance of limiting global warming to reaching any of the other goals and the fact that models addressing climate goals have started to expand their coverage to other SDG topics — often, by examining the co-benefits of mitigating climate change for other SDGs (von Stechow et al., 2016). In contrast, SDG5 (gender equality) and SDG16 (peace, justice, and strong institutions) are hardly addressed in the current set – especially due to challenges in quantifying the social and political processes that dictate the level of achievement of these goals. However, one could argue that progress toward these objectives is implicit in some scenarios. Interestingly, the overall distribution of papers per SDG reflects the distribution in other studies, including the model coverage of SDG thematic policy areas (Allen et al., 2016) and SDG coverage in IAMs (van Soest et al., 2019). There is clear clustering of the SDGs addressed in different studies (Figure 1c). The most common cluster of three contains SDGs 2, 15, and 13 ($N = 30$), representing the nexus between food, land/biodiversity, and climate. This cluster is also embedded in most larger clusters, often extended by SDG6 ($N = 17$) (clean water and sanitation), SDG7 ($N = 18$), SDG12 (responsible consumption and production) ($N = 16$), and SDG14 (life below water) ($N = 15$). A second frequent cluster is found around SDG7, SDG13, and SDG6 ($N = 20$). These clusters are mutually connected, and both are also directly linked to SDG3. SDG1 (no poverty), SDG8 (decent work and economic growth), SDG10 (reduced inequalities), SDG9 (industry, innovation, and infrastructure), and SDG11 (sustainable cities and communities) are loosely connected to these central clusters as well. The centrality of the food-land-climate and energy-climate nexus is correlated with the fact that these topics are well represented within the existing IAMs. Below, we elucidate some commonly used methods, themes, and indicators in the SDG scenario literature.

Progress toward SDG2 is commonly indicated by the number of people suffering from hunger or total food availability. Efforts to achieve zero hunger come in the form of a shift toward healthy, sustainable diets, reducing food waste (linked to SDG12), and assumed technological advances that lead to increased agricultural yields (Conijn et al., 2017; Hedenus et al., 2014). As indicated, SDG2 is often combined with SDG15 and SDG13, looking into trade-offs and synergies of climate and biodiversity strategies. Studies, for instance, show the connection between SDG2 and SDG15, in terms of land-use competition and synergistic measures (e.g. reducing food waste and dietary change). SDG2, SDG13, and SDG15 are also linked via carbon storage in ecosystems and possible degradation due to climate change.

A large group of papers ($N = 73$) addresses SDG13 via the climate goals of the Paris Agreement. Typically, such studies implement strategies by introducing a price on greenhouse gas emissions, often combined with further restrictions to avoid trade-offs with other SDGs (Grubler et al., 2018; Van Vuuren et al., 2018). Many of these papers investigate the relationship

https://doi.org/10.1017/sus.2023.20 Published online by Cambridge University Press

Table 1. Overview of seven studies addressing pathways toward achieving multiple SDGs

Study	Moallemi et al. (Moallemi et al., 2020)		Soergel et al. (Soergel, Kriegler, Weindl, et al., 2021)		Moyer et al. (Moyer & Bohl, 2019)		Van Vuuren et al. (van Vuuren et al., 2015)		Van Vuuren et al. (van Vuuren et al., 2017)		Grubler et al. (Grubler et al., 2018)		Randers et al. (Randers et al., 2019)	
Scenario	**SSP1***		**SDP (based on SSP1)**		**CC+DS+G**		**CC/DS/GT**		**SSP1***		**LED**		**BAU**	
	R	S	R	S	R	S	R	S	R	S	R	S	R	S
SDG 1				1		1						3	2	
SDG 2		4 6 7 9 10 11 12		13		14		4 8 14 15		5 9		9	16	
SDG 3		17 18 19		20		15		20 21 22 23		22 23		21 22	17	
SDG 4		25 26 27		28		24							25	
SDG 5				31									32	
SDG 6				33		36 37		34 35 36					37	
SDG 7	38 39 40 41	42 43 44 45		46		46		47 48 49		38 45 47		38 50 51	48	
SDG 8		52 53		55									54	
SDG 9				56						57			58	
SDG 10				60									61	
SDG 11				62									62	
SDG 12		63 64 66		67				64 67 69		67		59	68	
SDG 13	71 72 73 74	75 76 78		74 78		73		74 77 78		74 75 78		75 82	78	
SDG 14				80									79	
SDG 15		81 82 83		84 85				83		81 82		81 82 86	87	
SDG 16				88 89									90	
SDG 17				91									92	

For each study, the reference scenario (R) and most ambitious sustainability scenario (S) were selected. Colors indicate the level of goal achievement. Dark green indicates that a goal is met in the scenario; light green marks significant progress (~65–99%), yellow stands for moderate progress (~25–65%), orange indicates stagnation (~0–25% progress toward the goal), and red represents a worsening trend compared to today (<0%). Cells are colored grey when the results of multiple indicators for the same goal diverge. The numbers refer to the indicators used in the study to make the assessment, see Supplementary Information 3.

with SDG7 by looking into the impact of the share of renewable energies, improvements in energy efficiency, and relationships with universal access to modern energy services. The last, for instance, combined with the energy requirements to meet decent living standards (Grubler et al., 2018; Kikstra et al., 2021; Rao & Min, 2018).

SDGs 1 and 10 are often addressed by Gini indicators or poverty thresholds. Inequalities between countries, expressed in SDG10, are mostly covered via scenario assumptions on global GDP convergence across the SSPs. Poverty impacts of climate policy (SDG13) and the possibility to reduce inequality via revenue recycling are central themes in such studies (Fujimori et al., 2020; Soergel et al., 2021a, 2021b). The historical correlation between income levels, food demand, and household energy use is used in some studies to assess the projected food and energy supply gaps.

https://doi.org/10.1017/sus.2023.20 Published online by Cambridge University Press

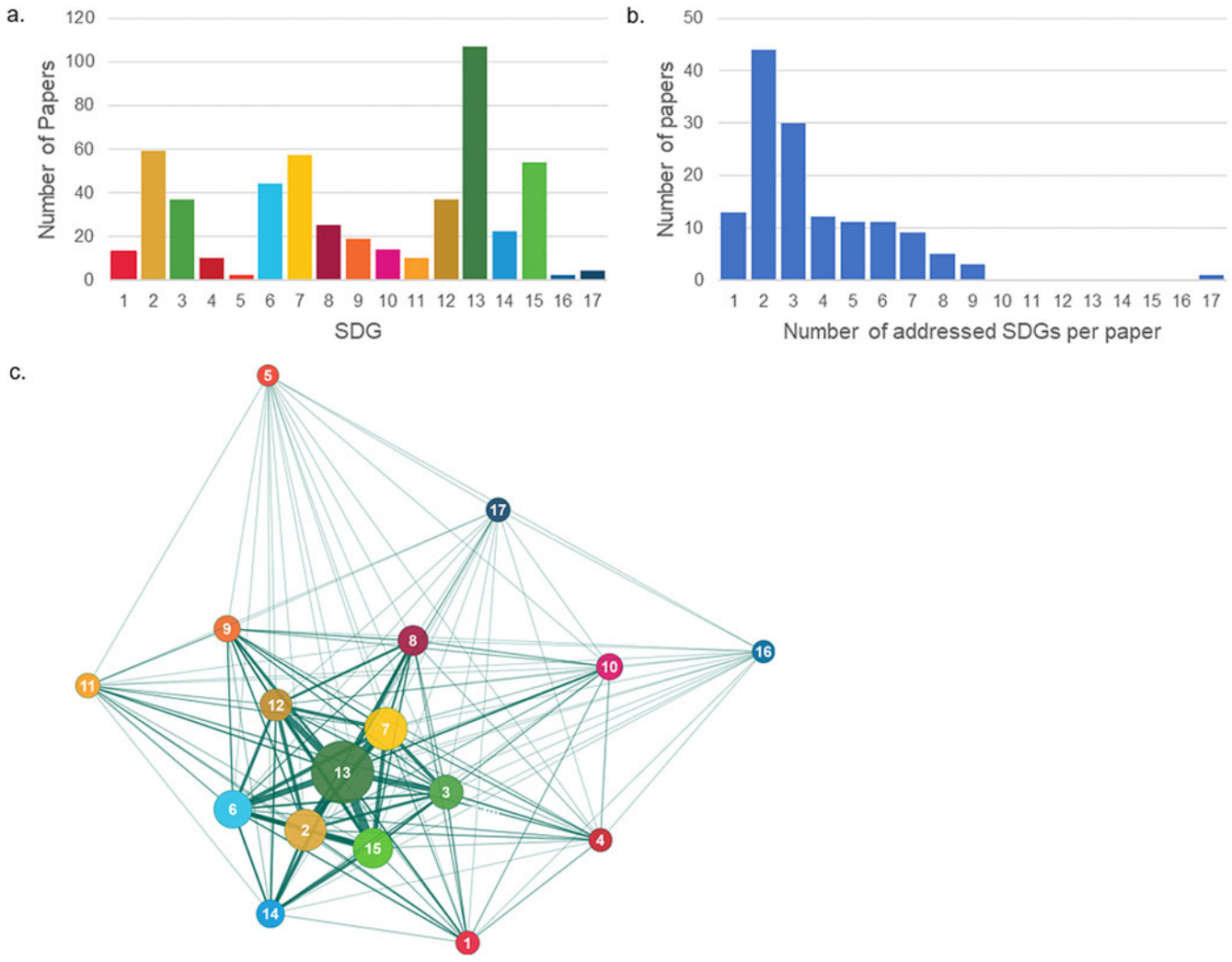

Figure 1. Overview of the 140 SDG scenario papers identified in the literature; (a) specific SDGs addressed in the scenarios, (b) the number of SDGs addressed in each specific study, and (c) a network presentation of the scenarios addressing multiple SDGs, the node size indicates the frequency of the goal, and the thickness of the edges scales with the number of co-occurrences between the goals.

Health and well-being are nearly always evaluated in terms of the impact of air pollutants on health, as measured by the mortality rate, premature deaths, or disability-adjusted life years attributed to either household or ambient air pollution. Here, the health benefits of reducing PM2.5 concentrations are often assessed for different climate policy scenarios relating to SDG11, through air pollution in cities. Indoor air pollution is mainly reduced through access to clean cooking, which in turn relates to SDG7.

Scenarios projecting increased access to sanitation, as expressed in SDG6, often use under-five mortality as an indicator and generally make significant progress toward this goal. Other SDG6 targets include increased efficiency in agricultural water use and limiting the number of people suffering from water stress. The latter is projected to worsen under multiple sustainable development scenarios due to climate change and population growth (Philippidis et al., 2020; van Vuuren et al., 2015), but less so than under business-as-usual.

Only a few studies cover a wide range of objectives related to the SDGs. We have selected seven particularly comprehensive sustainable development papers for further analysis (see Table 1, Supplementary Information). All include projections up to 2050, which allows for better coverage of the long processes involved. Three selected studies use the SSP1 narrative as a starting point and thus share many socio-economic assumptions and strategies to curb current negative trends. Van Vuuren et al. (2017) present the original SSP1 paper, exploring the impact of a sustainable development strategy based on green growth, combined with stringent climate policy. This study does not explicitly relate its results to the SDGs but covers a wide range of sustainability objectives. Moallemi et al. (2022) include a so-called 'green recovery' pathway based on a SSP1 scenario with climate policy stabilizing radiative forcing at 2.6 W/m^2 and gauges its results to the SDG targets. Soergel et al. (2021a, 2021b), also based on SSP1, is the only study that adds explicit sustainable development interventions to arrive at a sustainable development pathway toward all SDGs. Van Vuuren et al. (2015) take a different route and explores ways to reach six ambitious sustainability goals using three distinct policy pathways that rely mainly on technology, local solutions, or consumption change. Moyer and Bohl (2019) use the narrative assumptions of the Van Vuuren paper, together with a combination of the three strategies, but primarily focuses on human development. The authors explicitly

https://doi.org/10.1017/sus.2023.20 Published online by Cambridge University Press

state that they do not focus on goal achievement in itself, but explore to what extent human development goals are achieved under alternative scenarios. The Low-Energy-Demand scenario by Grubler et al. (2018) addresses a sub-set of SDGs, mostly in terms of the co-benefits of a low energy demand pathway to stay below 1.5 °C. Finally, Randers et al. (2019) assess the extent to which all the SDGs would be achieved by following current trends and, thus, do not seek to present pathways toward achieving the goals.

The projected outcomes of the various studies for the SDGs are qualitatively indicated in Table 1 for the reference scenario (without additional policies) and the most optimistic sustainable development pathway. The studies by Soergel et al. (2021b) and Randers et al. (2019) both address all SDGs, while the others each include either seven or eight goals. While there is a clear overlap between studies regarding the SDGs covered and the scenario assumptions, the studies use widely differing targets and indicators. For example, the indicator for gender inequality in Soergel et al. is the gender education gap in secondary education, while Moallemi et al. (2022) uses that same indicator (but in tertiary education) for SDG4. Therefore, seemingly, gender is covered by the former and not by the latter, although they use the same indicator. Similarly, the studies typically use very different indicators for those SDGs covered by all studies, such as SDGs 2, 3, 7, 12, and, to some degree, SDG15 (for other SDGs, such as SDGs 1 and 13, there is somewhat more overlap). This lack of harmonization poses a challenge to comparing the respective scenarios.

For our assessment of progress of achieving the SDGs, we adopted the targets and indicators used in the studies to indicate the progress toward and achievement of the SDGs by 2050, per scenario study, on its own terms where possible (see methods). The projections indicate that the situation would worsen under reference scenario conditions for all environmental SDGs. For many human-development SDGs, progress is projected to be moving into the right direction but will be insufficient to meet the goals. In the sustainable development scenarios, progress toward the SDGs is, by definition, better. Still, most studies report insufficient improvement on numerous goals (including environmental SDGs). That said, not all indicators are equally representative of the goals, and the choice of indicator heavily influences the outcome.

4. Conclusion

In summary, the SDGs, so far, have largely been treated as a co-benefit of climate policy or included implicitly as part of certain scenario narratives. There are currently only a few studies that explore pathways toward a broad set of SDGs, providing little support for policymakers on what is needed to meet the SDGs, the possible synergies and trade-offs, or the required level of effort. The few studies available use a remarkably diverse set of targets and indicators to measure SDG achievement. This significantly reduces the quality and validity of comparison (and thus limits the possible insights). Consequently, there is a need for scenario literature that explores a wide set of pathways toward achieving multiple SDGs, preferably based on a standardized framework of quantifiable targets and indicators (e.g. the sustainable development Target Space [van Vuuren et al., 2022]) to help scenario assessment and future collaboration. Such new scenarios could build on the existing work on synergies and trade-offs, and combine the clusters of goals identified in Figure 1 to cover a much wider set of SDGs, addressing issues such as integration with well-being (Rao & Wilson, 2022), and improve the representation of demand-side solutions (Creutzig et al., 2018; van den Berg et al., 2019). Using a broader set of socio-economic and technological pathways could lead to more robust insights into possible pathways toward sustainability and a broader exploration of the social, political, and technological space leading to the achievement of the SDGs. Collaboration across various model and scientific paradigms might provide the necessary insights to model SDGs that are currently poorly represented, improve the representation of the dynamics that drive the achievement of the SDGs, and create a new standard for scenario generation.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/sus.2023.20.

Acknowledgements. None to declare.

Author contributions. K. O. and D. P. v. V. designed the study and wrote the original draft. K. O., D. P. v. V., G. A., S. K., E. W., V. Z., and C. Z. gathered and analyzed the literature. K. O. and V. Z. processed the data. All authors contributed to the writing manuscript.

Funding statement. The paper benefitted from funding from the European Research Council under grant no. ERC-CG 819566.

Competing interests. None.

Research transparency and reproducibility. The literature database has been made available as Supplementary Information 2.

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https://doi.org/10.1017/sus.2023.20 Published online by Cambridge University Press