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Policy mixes for sustainable development pathways: representation in integrated assessment models

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Abstract

The Paris Agreement on climate change and the 2030 Agenda on Sustainable Development require unprecedented transformations to sustainability, while maximising synergies and minimising trade-offs between the two agendas. The policy studies and sustainability transition literatures suggest that addressing the complex policy interlinkages requires ambitious, coherent, comprehensive and credible policy mixes supported by synergistic combinations of governance modes. We investigate to which extent these assumptions are reflected in quantitative scenarios produced with integrated assessment models. As a case study, we assess a new set of target-seeking sustainable development pathway (SDP) scenarios. We scrutinise the modelling protocols and the scenario results to analyse the extent to which these modelled SDPs represent governance modes and policy instrument types and purposes, and assess the resulting policy mix characteristics. As such, we bridge the scenario modelling and policy mix literatures and provide an initial pathway appraisal. We find that the modelled SDPs use policy mixes to constrain negative side-effects of unmitigated climate measures to achieve several SDGs simultaneously. The policy mixes speak to several policy mix characteristics. However, they are only partially spelled so far and their credibility remains limited. This calls for additional policy-translation efforts.

1. Introduction

The implementation of the Paris Agreement on climate change and the 2030 agenda on sustainable development with its 17 sustainable development goals (SDGs) requires unprecedented rapid and deep transformations. While developed separately, the two agendas are strongly interlinked, as action taken on either of them can support or hinder the other (Iacobuţă *et al* 2021, Lee and Romero 2023). Both the policy studies and the sustainability transition literatures suggest that addressing complex policy interlinkages can best be achieved through ambitious, coherent, comprehensive and credible policy mixes (Hood 2011, Weber and Rohracher 2012, Rogge and Reichardt 2016, Howlett and Saguin 2018, Kern *et al* 2019, OECD 2023) and related combinations of different governance modes (hierarchies, markets, networks; see below) (Pahl-Wostl 2019).

Integrated assessment models (IAMs) have been important tools to quantify pathways towards the Paris climate target and are increasingly also used to identify pathways combining climate action with a broader set of sustainable development goals (Soergel *et al* 2021). Multiple sustainable development pathways (SDPs) are conceivable (Aguiar *et al* 2020), depending on underlying societal values, regional priorities, economic paradigms and governance factors.

Nevertheless, while they are indispensable tools, IAMs have faced with various limitations towards modelling SDPs. Critiques on past IAM scenarios included their focus on an unrealistic uniform global carbon price as the main policy instrument (Kriegler *et al* 2018, Brutschin and Andrijevic 2022, Hickmann *et al* 2022), feasibility concerns (Brutschin *et al* 2021, Perino *et al* 2022) as well as the limited representation of policy mixes and innovation (Keppo *et al* 2021) and of political and governance factors and processes (Andrijevic *et al* 2020, Leininger *et al* in review, Pianta and Brutschin 2022). If effective policy mixes are key for achieving multiple policy goals simultaneously, it is essential to better understand the representation and shortcomings of policy mixes in modelled SDP scenarios for adequate translation into practice.

This paper therefore inquires what the explicit and implicit assumptions on governance modes and policy mixes in quantified SDPs are and how these relate to a set of key policy mix characteristics as identified in policy studies. As object of study, here we focus on three archetypal scenarios that have been designed for a structured model comparison of SDPs: (1) a market-oriented green-growth pathway ('Economy-driven Innovation', SDP-EI); (2) a sufficiency-oriented post-growth pathway ('Resilient Communities', SDP-RC); (3) a government-driven global commons-oriented pathway ('Managing the Global Commons', SDP-MC). The newly developed narratives behind these SDPs are presented in Kriegler *et al* (in preperation). Based on these narratives, Soergel *et al* (2024) quantified three SDPs bringing together a set of IAMs and industrial ecology models. This new suite of target-seeking scenarios intends to broaden the existing scenario space of shared socioeconomic pathway (SSP)—representative concentration pathway (RCP) combinations (Riahi *et al* 2017) by including a much broader set of targets based on the 2030 Agenda's SDGs alongside ambitious climate action (O'Neill *et al* 2020). Our inquiry constitutes an appraisal of the modelling exercise from a policy studies' perspective and helps to explore what realising the scenarios in practice would imply for policy design.

2. Literature review and analytical framework

We base our analytical framework on a review of social sciences literature on policy mixes, mainly drawing on policy studies, governance studies, and transition studies, but also including insights from economics. Policy mixes are comprised of elements (strategy and instrument mixes), policy processes and characteristics of elements and processes (Rogge and Reichardt 2016). A policy strategy consists of goals and means of implementation, i.e. policy instruments, while the instrument mix consists of several interacting policy instruments. We are particularly interested in the policy instruments and characteristics of instrument mixes needed to achieve SDPs.

Policy instruments are frequently categorised across three *instrument types*: economic, regulatory and information instruments, which are typically assessed against effectiveness, efficiency, equity and feasibility criteria (Rogge and Reichardt 2016, see table 1). Regulatory instruments are based on command-and-control policies, and theoretically able to meet certain targets, but often go along with high enforcement costs and acceptability issues. Economic instruments are intended to correct market failures through internalisation of external costs. In particular, environmental taxes and tradable permits are considered efficient and effective (Requate 2005, Baranzini *et al* 2017), but acceptability is often low. Subsidies have high acceptability but can be costly. Information (or persuasive) instruments target voluntary behavioural changes and social learning, but they may not reach uninterested or resisting parties (e.g. Bouwma *et al* 2015). Hybrid instruments (table 1) rely on at least two actor types (state, private sector or civil society) (Koontz and Thomas 2006) and thus combine related governance modes (hierarchies, markets, networks). Often hybrid instruments are considered more innovative and effective (Lemos and Agrawal 2006, p 311).

Policy instruments are also categorised based on three key *instrument purposes*: technology push, demand pull and systemic (Rogge and Reichardt 2016, table 1). Instruments with technology push purpose directly support technological innovation and adoption, by addressing both research and development as well as market entry and diffusion. Instruments with demand pull purpose seek to influence consumer behaviour, for example by prohibiting certain products or resources, providing product performance information, or incentivising behaviour through taxes and subsidies. Instruments with systemic purpose support 'functions operating at system level' (Smits and Kuhlmann 2004), such as building and organising systems. They can be particularly effective in breaking path-dependencies and may create the enabling environments for the adoption of new technologies and consumer behaviour.

Policy development and implementation takes place within a given governance context. *Governance modes* represent the coordinating principles through which decision-making is realised (Pahl-Wostl 2019). Hierarchies, markets and networks represent Weberian ideal types that relate to specific societal preferences for policy instrument types (Meuleman 2008, Howlett 2009, Pahl-Wostl 2019). In hierarchies, coordination is achieved through top-down orders, e.g. in bureaucratic organisation or firms (Williamson 1999), with a preference for regulatory instruments. In markets, prices coordinate exchange

Table 1. Types and purposes of policy instruments. Adapted from Rogge and Reichardt (2016). CC BY 4.0.

	Primary Purpose		
Primary Type	Technology push	Demand pull	Systemic
Economic instruments	RD&D[a] grants and loans, tax incentives, state equity assistance	Subsidies, feed-in tariffs, trading systems, taxes, levies, deposit-refund-systems, public procurement, export credit guarantees	Tax and subsidy reforms, infrastructure provision, cooperative RD&D grants
Regulation	Patent law, intellectual property rights	Technology/ performance standards, prohibition of products/ practices, application constraints	Market design, grid access guarantee, priority feed-in, environmental liability law
Information	Professional training and qualification, entrepreneurship training, scientific workshops	Training on new technologies, rating and labelling programs, public information campaigns	Education system, thematic meetings, public debates, cooperative RD&D[a] programs, clusters
Hybrid	Public-private partnerships	Payments for ecosystem services, cap and trade	Co-management

[a] RD&D = Research, development and demonstration.
Source: adapted from Rogge and Reichardt (2016).

between self-interested actors (Williamson 1985). Societies that strongly rely on markets tend to prefer economic instruments. In networks, coordination is based on mutual interdependencies, trust and actors' responsibilities (Bouckaert *et al* 2010), with a preference for information instruments. Emerging evidence suggests that complex governance challenges are more effectively addressed through synergistic combinations of governance modes than dominance of a particular governance mode (Lukat *et al* 2023).

While the economics literature assumes that ideally a policy goal can be achieved by one policy instrument (Tinbergen 1952), the policy mix literature emphasises that given market and other system failures, often a mix of policies is needed to achieve a goal (Lehmann 2010, Weber and Rohracher 2012, Rogge and Reichardt 2016). SDPs for the 2030 Agenda address multiple ambitious climate and sustainable development goals that require various policy levers within and across sectors. The 'Tinbergen rule' says that for several goals at least one instrument for each goal is needed (Tinbergen 1952, Knudson 2009, Del Rio and Howlett 2013). To address the complexity of these goals, coherent mixes of policy instruments ('policy mixes') are necessary, even if in some cases, a single policy instrument (e.g. a carbon tax) may contribute to several goals (Knudson 2009).

The policy mixes literature points to several policy mix characteristics, which are likely to support sustainability transitions (Kivimaa and Kern 2016, Rogge and Reichardt 2016, Howlett 2019). We cluster characteristics that allow for a static and dynamic analysis of the policy mix respectively (table 2). The characteristics can be considered as prerequisites for policy mixes to achieve the policy instrument assessment criteria effectiveness, efficiency, equity and feasibility (Rogge and Reichardt 2016).

From a static perspective, looking at the features of the mix at a given point in time, key characteristics include policy coherence, including consistency of instruments, and comprehensiveness. While authors define and use the terms coherence and consistency slightly differently (e.g. Nilsson *et al* 2012, Rogge and Reichardt 2016, Howlett 2019), we use *policy coherence* as the overarching term and refer to *consistency of instruments* when analysing their interactions. We speak of *comprehensiveness* when the policy mix comprises instruments with technology push, demand pull and systemic purposes (Rogge and Reichardt 2016).

From a dynamic perspective, analysing how the policy mix evolves over time, smart policy sequencing is essential for overcoming old path dependencies and creating new paths that raise ambition and prove durable. Policy mixes should provide directionality and nurture innovation, expand and mainstream alternatives, and address the key challenge of breaking out of the incumbent arrangements and respective path dependencies. Kivimaa and Kern (2016) note the need for *creative destruction,* both creating new policies that support innovation (e.g. R&D funding, training, innovation platforms) and mainstream it (e.g. subsidies, tax exemptions, feed-in-tariffs), and removing conflicting policies (e.g. fossil fuel subsidies). Creative destruction may be necessary to ensure coherence between objectives in a policy mix, as negative interactions may appear between old and new policies (Rogge *et al* 2017, Howlett 2019). Moreover, creative destruction might face resistance by vested interests and require compensatory measures (e.g. safety nets, carbon price revenue recycling) that address the negative impacts of removing old or introducing new policies (Iacobuţă *et al* 2021, Hägele *et al* 2022). To ensure that the desired sustainability

Table 2. Key concepts related to policy mixes characteristics.

Concepts related to static characteristics	
Policy coherence	An overall state of mutual consistency among different policies (OECD 1996). An attribute of policy that systematically reduces conflicts and promotes synergies between and within different policy areas to achieve the outcomes associated with jointly agreed policy objectives (Nilsson *et al* 2012, p 396).
Consistency of policy instruments	Complementarity ($X + Y = 2$) or even synergy ($X + Y > 2$) among instruments (Del Rio and Howlett 2013).
Inconsistency of policy instruments	Weak conflict ($1 < X + Y < 2$) or strong conflict ($0 < X + Y < 1$) among instruments (Del Rio and Howlett 2013).
Comprehensiveness	The extent to which a policy mix addresses all market, system and institutional failures (Weber and Rohracher 2012); may comprise of instruments that address all three purposes—technology push, demand pull and systemic (Rogge and Reichardt 2016).
Concepts related to dynamic characteristics	
Policy sequencing	A process that incrementally relaxes or removes barriers over time and introduces new measures to enable significant increases in policy stringency (Meckling *et al* 2017, Pahle *et al* 2018).
Creative destruction	Creation of policies that support new pathways and the removal of policies that keep old patters in place (e.g. fossil fuel subsidies) (Kivima and Kern 2016).
Robustness	Ability of a policy mix to adapt to a variety of future challenges, in particular foreseeable ones, e.g. through a redundancy of instruments, maximising complementary effects (Howlett 2019).
Resilience	Ability of a policy mix to adapt in the face of shocks and withstand potential opposition or conflict, for instance through safety nets (Howlett 2019).
Overarching characteristic	
Credibility	The degree to which actors believe that a given policy mix will be implemented and how it takes into account governance contexts (Rogge and Reichardt 2016).

Source: own compilation.

transformations not only overcome old path dependencies, but become new lasting path dependencies, *robustness* and *resilience* are needed (Howlett 2019). Policy sequencing can increase robustness through redundancy of instruments and strengthen resilience through safety nets and procedures that allow for adjustments as conditions change, e.g. built-in reviews (Howlett 2019).

To ensure success, a policy mix also needs to have *credibility* by accounting for the context of its implementation. Various factors can influence policy implementation, such as political regime type, rule of law, electoral cycles, political leadership commitment, institutional quality (government effectiveness and good governance) or public acceptability (Rogge and Reichardt 2016, Andrijevic *et al* 2020, Soergel *et al* 2021, Leininger *et al* in review).

3. Methodology

We analyse the representation of policy instruments and the characteristics of policy mixes in three quantified SDP scenarios based on their implementation in the two IAMs REMIND-MAgPIE and IMAGE as presented in Soergel *et al* (2024). Key features of the narratives behind these scenarios are summarised in table 3. From a governance perspective, the three scenarios, SDP-EI, SDP-RC, SDP-MC, were designed to reflect a dominance of each of the three governance modes—markets, networks and hierarchies—respectively, while acknowledging that they do not appear in pure forms and that synergistic combinations may be desirable (Pahl-Wostl 2019). Further governance assumptions in the narratives—that are underpinned by this paper's literature review—are provided by table 3.

The analysis builds upon an iterative process of social scientists and modellers in the development and analysis of the SDPs. Figure 1 shows the interactions between social scientists and modellers and the inputs and analyses emerging from and for this paper at each stage of the scenario development process. Our analytical framework is based on our literature review (previous section) and analyses the representation of policy instrument types and purposes and governance modes in modelled SDPs and their policy mix characteristics. The analysis draws on interviews with modellers and on an in-depth scrutiny of modelling implementation protocols and modelling results for REMIND-MAgPIE and IMAGE. As part of this, we systemically sorted all interventions listed in the model implementation protocol of the REMIND-MAgPIE model (Soergel *et al* 2024) according to explicit economic instruments, interventions likely

Table 3. Key features of the SDP narratives. Adapted from Soergel *et al* (2024). © The Author(s). Published by IOP Publishing Ltd CC BY 4.0.

Scenario title and narrative summary	Economic outlook	Energy & materials	Food & land	Governance outlook
SDP-EI: Economy driven Innovation (EI) 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 ▪ 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	▪ Markets as key drivers of innovation, opportunity and wealth ▪ States as regulators to align market outcomes with societal objectives ▪ Preference for economic instruments ▪ Effective government, rule of law ▪ Peace prevails
SDP-RC: Resilient Communities (RC) 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 ensure 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	▪ Networks of communities, civil society, private sector and (sub-) national authorities as main drivers of transformation ▪ States as partners to support community development and resource sharing ▪ Preference for information instruments ▪ Effective government, rule of law ▪ Peace prevails
SDP-MC: Managing the Global Commons (MC) to ensure sustainable development *In this world, a global world view 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-emphasised. Peace prevails.*	▪ Moderate economic growth in Global North, high growth in Global South, strong convergence ▪ Fast reductions of inequality	▪ Medium demand for energy services, high efficiency ▪ Medium material demand ▪ High recycling rates	▪ 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	▪ Governments (hierarchies) as main driver of transformation ▪ States and global institutions as leaders and orchestrators ▪ Preference for regulatory instruments ▪ Effective government, rule of law ▪ Peace prevails

Source: adapted from Soergel *et al* (2024) and Kriegler *et al* (in preperation).

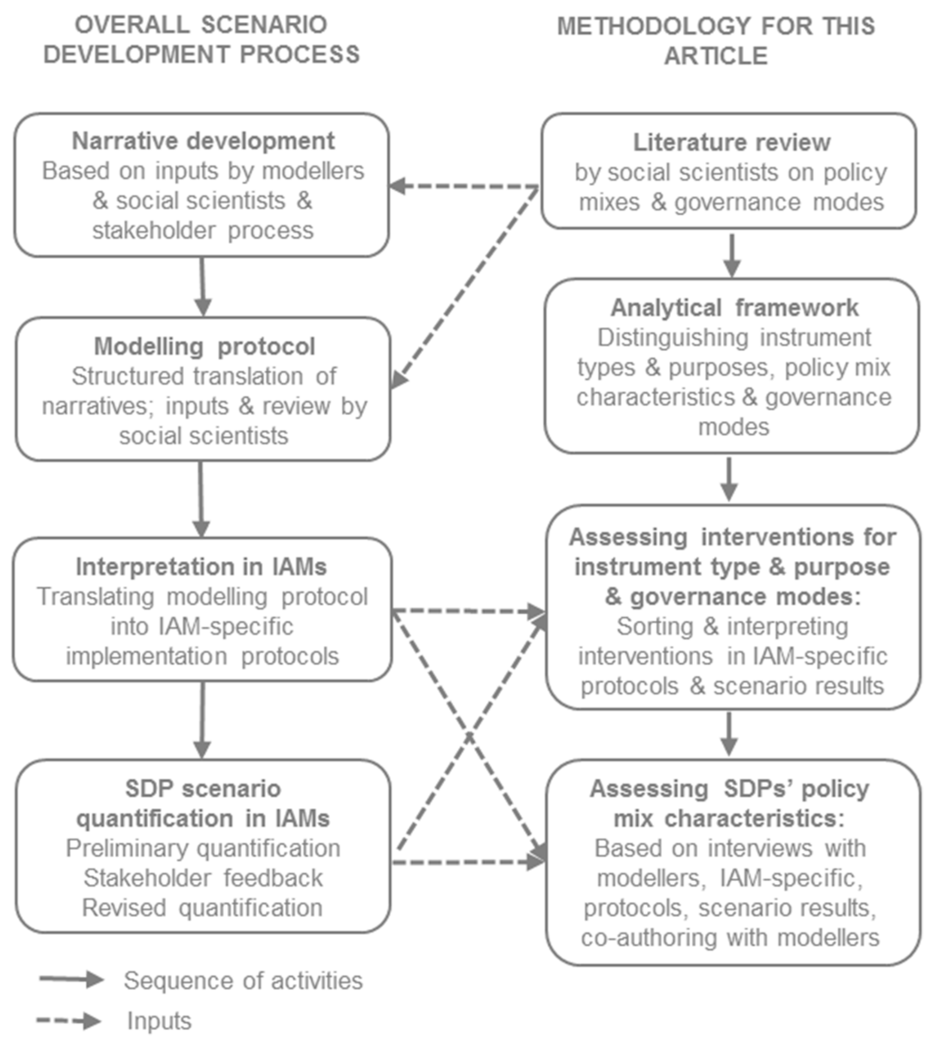

Figure 1. SDP scenario development process and methodology for this article and their interactions. Adapted from Soergel *et al* (2024). © The Author(s). Published by IOP Publishing Ltd CC BY 4.0.
Source: own presentation, left column adapted from Soergel *et al* (2024).

to involve economic and/or regulatory instruments, and interventions for which instrument types are undefined. We also attributed them to ten different intervention areas, depicted by different icons (see supplementary material and table 4 in results section).

4. Results: governance modes and policy instruments and mixes in SDPs

4.1. Policy instrument types and governance modes in SDP interventions

As 'target-seeking' scenarios, the models mimic various interventions by either explicitly representing distinct policy instruments or assuming adjustments to model parameters. The SDP quantifications explicitly use economic instruments. This includes, most notably, carbon pricing across sectors, but depending on the model implementation, also a bioenergy tax, a final energy tax, and final energy subsidy phase out. The quantified scenarios furthermore include various bans (e.g. on forms of forest clearance), limits (e.g. on bioenergy use) and protection measures (e.g. for biodiversity hotspots and environmental flows). Bans, limits and protection measures can be interpreted as regulatory instruments, although limits could sometimes also be achieved through other measures (see forest example below). Parameter adjustments relate to efficiency increases (e.g. in soil nitrogen uptake or buildings' thermal efficiency) as well as behavioural changes (e.g. diets, area of used floor space, cooling and heating demand, transportation mode choices) or infrastructure and technological innovations (e.g. electrification rates, material use intensity, carbon capture storage (CCS) for which the instrument types are undefined and different types and mixes could be chosen based on the respective scenario narratives (table 5). Information and hybrid instruments are not explicitly part of the model implementation, but they are expected implicit measures, especially in the SDP-RC scenario. Table 4 and the supplementary material provide examples of

Table 4. Selected interventions in quantified SDPs sorted by policy instrument types (REMIND-MAgPIE). Adapted from Soergel *et al* (2024).

	SDP-EI	SDP-RC	SDP-MC
	Explicit economic instruments		
	• Uniform carbon price for all sectors to reach 1.5° target, increasing over time; level depending on other interventions; regional prices converge by 2050 • Level of international carbon price revenue recycling: 12.5%	• Uniform carbon price for all sectors to reach 1.5° target, increasing over time; level depending on other interventions; regional prices converge by 2060 • Level of international carbon price revenue recycling: 12.5%	• Uniform carbon price for all sectors to reach 1.5° target, increasing over time; level depending on other interventions; regional prices converge by 2050 • Level of international carbon price revenue recycling: 50%
	Interventions likely to involve economic and regulatory instruments		
	• Re/afforestation with a global upper limit of 350 Mha, following plantation growth curves. Beyond NDC targets, re-/afforestation driven by carbon prices	• No further re-/afforestation beyond NDC targets; natural regrowth of vegetation on abandoned land	• Re-/afforestation with native species following growth curves of natural vegetation with a global upper limit of 700 Mha. Beyond NDCs targets, re-/afforestation driven by carbon prices
	• Soil nitrogen uptake efficiency: increase due to strong technological and managerial progress and based on marginal abatement costs	• Soil nitrogen uptake efficiency: increase due to medium technological and managerial progress and based on marginal abatement costs	• Soil nitrogen uptake efficiency: increase due to strong technological and managerial progress and based on marginal abatement costs
	Interventions likely to involve regulatory instruments		
	• Protected areas: current levels	• Protection of biodiversity hotspots and intact forest landscapes	• Protection of biodiversity hotspots
	• Global bioenergy limit: 300 EJ yr^{-1}	• Global bioenergy limit: 100 EJ yr^{-1}	• Global bioenergy limit: 150 EJ yr^{-1}
	• CCS: Max. 0.5% of estimated storage capacity, ∼20 Gt CO_2/yr globally	• CCS: Max. 0.1% of estimated storage capacity, ∼4 Gt CO_2/yr globally	• CCS: Max. 0.25% of estimated storage capacity, ∼10 Gt CO_2/yr globally
	• Cars: phase-out of diesel engines by 2040; trucks: strong phase down	• Cars: combustion engine phase-out by 2040; trucks: phase down	• Cars: phase-out of diesel engines by 2040; trucks: strong phase down
	Interventions with undefined policy instruments		
	• Dietary changes: substituting 50% of per-capita ruminant meat consumption with microbial protein and overcoming underweight by 2050	• Dietary changes: gradual shift to EAT-Lancet diets in 2050, with total calorie intake consistent with a healthy body weight	• Dietary changes: gradual shift to EAT-Lancet diets in 2070, with total calorie intake consistent with a healthy body weight
	• Regional reduction in food waste by 2050 if an upper limit is exceeded; minus 25% relative to current levels in high-income regions	• Regional reduction in food waste by 2050 if an upper limit is exceeded; minus 50% relative to current levels in high-income regions	• Regional reduction in food waste by 2070 if an upper limit is exceeded; minus 38% relative to current levels in high-income regions

(Continued.)

Table 4. (Continued.)

	• Reduced energy demand in buildings: building shells reach higher efficiency in the long term; default efficiency of devices; lower hot water consumption	• Reduced energy demand in buildings: default efficiency of building shells and devices; extremely low hot water consumption	• Reduced energy demand in buildings: reach very high efficiency of building shells and devices in the long term; very low hot water consumption
	• Residential floor space growth capped at 75 m^2/cap	• Residential floor space growth capped at 40 m^2/cap	• Residential floor space growth capped at 50 m^2/cap
	• Increased share of high-speed rail; medium demand for cars; default reduction of domestic aviation	• Strong change of preferences in favour of public transport, active modes and smaller cars; strong reduction of domestic aviation	• Change of preferences in favour of public transport, active modes and smaller cars; strong reduction of domestic aviation
	• High demand for steel, cement & other materials in industry	• Low demand for steel, cement & other materials in industry	• Medium demand for steel, cement & other materials in industry
	• Energy system capital stock that can be retired early: strongly increased	• Energy system capital stock that can be retired early: default (as SSP2)	• Energy system capital stock that can be retired early: increased

Source: based on the REMIND-MAgPIE modelling implementation protocol (Soergel *et al* 2024); sorted according to policy instrument types; description was shortened, and sector icons were added; the Supplementary Material to this article sorts all interventions in REMIND-MAgPIE.

important interventions sorted by instrument type and how they vary over the three modelled SDPs. The analysis shows that for most interventions policy instrument types are not yet specified.

Overall, the models simulate markets with different levels of regulation according to the three scenarios. This implies that in terms of governance modes, markets are explicit whereas hierarchies are explicitly and implicitly represented in the models. Networks are not represented, but depending on the scenario narratives they can be assumed to play an important role. Hence, the modelled SDPs at least indirectly mimic all three governance modes to various degrees.

The carbon price in the SDPs is endogenously determined based on the carbon budget for the 1.5 °C target and taking all other interventions into account. The resulting price is thus reflective of the additional mitigation effort needed beyond the other interventions. In the long run the carbon price is the lowest in SDP-RC (200-250 \$/tCO_2 in 2100, given range is across the two IAMs) (Soergel *et al* 2024), where behavioural changes (e.g. in transport choices, diets, floor space and energy consumption) ease the mitigation effort. Carbon pricing is highest in the SDP-EI (about 410-570 \$/tCO_2 in 2100), where carbon pricing reduces energy demand to some extent and mitigation is complemented by efficiency improvements and supply of mitigation technology. SDP-MC with a carbon price of 260-400 \$/tCO_2 in 2100 harvests synergies between demand-side shifts, efficiency increases and supply-side mitigation options. By contrast, in 2050 all three scenarios have a similar carbon price of around 200 \$/tCO_2 for REMIND-MAgPIE and slightly lower for IMAGE (Soergel *et al* 2024), as SDP-RC relies on this carbon price to make up for reduced availability of mitigation technologies (e.g. bioenergy, CCS).

The forest sector is another example where the SDP scenarios vary in their assumptions on policy instruments. For REMIND-MAgPIE afforestation in SDP-EI is driven by the carbon price (i.e. as carbon offsetting) and has the least restrictions regarding how the afforestation projects are carried out, allowing for faster-growing plantations. A global limit of 350 million hectares for SDP-EI avoids land-use conflicts driven by large-scale plantation afforestation. In the SDP-MC scenario, however, the economic optimisation of the model results in afforestation levels that are lower than the given global limit of 700 Mha (Soergel *et al* 2024). This example shows that a limit in the modelling protocol does not necessarily need to translate into a required regulatory instrument. SDP-MC has in the long run broadly similar afforestation areas compared to SDP-EI, but vegetation growth is slower, only allowing for native species and hence involving an additional assumption on regulation. Hence, for SDP-EI and SDP-MC the model assumes different mixes of economic and regulatory instruments. In the SDP-RC scenario, there are no economic incentives for afforestation, so that the afforested areas do not exceed the values of the nationally determined contributions (NDCs) under the Paris Agreement. However, if agricultural land is abandoned, natural regrowth can lead to an additional increase in forest cover without further human intervention. According to the SDP-RC narrative this could be supported through regulation or information, but most likely information

Table 5. Policy implications and instrument options for interventions with undefined policy instruments.

Modelled intervention	Policy implication	Possible policy instrument options		
		SDP-EI	SDP-RC	SDP-MC
Regional reduction in food waste by 2050 if an upper limit is exceeded (minus 25% relative to current levels in high-income regions in SDP-EI, 50% in SDP-RC, 38% in SDP-MC)	Food losses and waste will need to be addressed across the whole food chain, from farm to fork. This may include regulations to use harvest waste/by-products for other purposes, e.g. energy production; to shorten transportation distances and reduce waste during transportation; to increase the share of produce being sold, e.g. incentivise sale of 'ugly' vegetables; support better connection between local farmers and distributors. Shifts strongly rely on behavioural change with limits to what policy can achieve.	Subsidies for use of waste for energy production, livestock feed or other uses; taxation of perishable long-distance products; investments in RD&D for enhanced food storage technologies and for AI systems that improve timely usage (e.g. smart fridges).	Product labels where production process involves high waste reduction; preferential support for local food cooperatives; campaigns to consume aesthetically substandard vegetables; food waste reduction information campaigns.	Investments in waste-to-energy power plants; grid access guarantee for waste-to-energy producers; support of local food products, e.g. via required minimum share in supermarkets; requirements for improved food storage systems.
Dietary changes: 50% substitution of ruminant meat with microbial protein in SDP-EI; transition to EAT Lancet diets by 2050 in SDP-RC and by 2070 in SDP-MC	Policies need to incentivise consumption of vegetables/non-animal products and to disincentivise livestock products. Support for the development and adoption of alternative food products will be needed. Food prices will need to be monitored, and social support may be needed to ensure that new policies do not increase hunger, but rather reduce it. Shifts strongly rely on behavioural change with limits to what policy can achieve.	Investments in RD&D for animal-free alternatives; taxation of animal products; subsidies and tax breaks for emerging animal-free alternatives.	Campaigns and (school) education for healthy and environmentally friendly diets; environmental and health-related food labels; support for local food cooperatives.	Limit on available land for livestock; measures to improve demand and supply systems for desired products; restricted advertising of sugar-rich and heavily processed foods.

(Continued.)

Table 5. (Continued.)

Reduced energy demand in buildings (e.g. building shells efficiency, devices efficiency, hot water consumption)	Policies need to incentivise a switch to higher electrification and the uptake of more efficient appliances, improvements in buildings insulation, increased efficiency of energy-related systems (including for heating/cooling spaces and water) and the adoption of smart-home technologies that can better control consumption. Some of these measures are costly (although efficient in the long term) and will be dependent on income-levels if additional financial support is not available.	Investments (grants and loans) in RD&D for energy efficient options; taxation of energy use (constant or progressive); tax breaks and other incentives for buildings upgrades intended to overcome tenant-landlord dilemma.	Subsidies and information campaigns for smart metering and other smart home systems; campaigns and education on low-energy use lifestyles, e.g. reduced hot water consumption; labelling of appliances' energy consumption; buildings energy efficiency labels; creation and promotion of co-working and co-living spaces.	Prohibition of inefficient appliances; energy efficiency codes and standards for buildings, heating systems and appliances; requirement to use electric heating; investments in energy efficiency improvements of public buildings.
Reduced energy demand in transport (i.e. increased use of public transport; higher load factor for cars (SDP-RC); phase-down and -out of diesel engine vehicles; transport electrification)	Policies need to effect changes in types of vehicles, transport modes, and demand for transportation. While vehicle efficiency may continue to be improved, there is a limit to this approach and a phase down and phase out of diesel engines and an increase in electric vehicles based on renewables will be needed. Transport modes with higher loads will need to be developed and incentivised, such as public transport, shared autonomous vehicles, or car load increase. Improved infrastructure should enhance flow and adoption of desired modes of transport, e.g. bike lanes. Long-distance travels should be reduced. The high need for behavioural changes may limit policy capabilities.	Investments for RD&D of improved electric vehicles, autonomous vehicles, digital technologies; Subsidies for electric and autonomous vehicles; Increased taxes on the use of fossil fuels in transport; Fiscal/financial support for autonomous car sharing start-ups.	Campaigns to support increased car loads and public transport; car-free designated areas; public transport options included in the social security system; public transport investments; cycling infrastructure investments; education on health and environmental benefits of cleaner and more active modes of transportation.	Investments in public transport systems quality and connectivity; investments in infrastructure to accommodate new modes of transport and vehicle types; mandatory electric vehicle charging stations in parking lots; energy efficiency standards for vehicles; shift to electrified transport in public services.

Source: own compilation.

instruments will not be sufficient, and regulation would be needed. Sometimes, the two IAMs also differ in the exact instrument mix to achieve a certain target. For instance, REMIND-MAgPIE uses a mix of regulation and carbon pricing to disincentivise CO_2 emissions from land-use change for the protection of terrestrial ecosystems, while IMAGE assumes different protection targets for different types of terrestrial ecosystems.

Overall, the degree to which models directly represent specific policy instrument types remains limited. This limits guidance for policymakers on how to translate such scenarios into practical implementation but provides flexibility and points at the multitude of possible pathways. For illustration, table 5 presents three examples of interventions for which instruments are undefined in the models and discusses possible policy instrument options that are likely to be preferred in each of the three SDPs.

4.2. Policy instrument purposes in SDP interventions

We also analysed to what extent the modelled SDPs draw—at least implicitly—on the three policy instrument purposes technology push, demand pull and systemic. In all SDPs, externality pricing (in particular, pricing of greenhouse gas emissions) is a key policy instrument exerting a demand pull, by making CO_2 intensive technologies more expensive and carbon-free technologies more competitive. Given that the carbon price is highest in SDP-EI, this scenario has the highest uptake of certain technologies (e.g. solar, wind, bioenergy and CCS in both IAMs, hydropower and nuclear in IMAGE). In addition, SDP-EI features an increased CCS capture rate and faster technology innovation rates, which can be interpreted as the result of technology push policies, but policy instruments are not explicit. Hence, technological change is primarily achieved through demand pull, but also, although to a lesser extent, through technology push. All scenarios assume demand pull through externality pricing, but the extent varies with the carbon price. In addition, demand changes may come about intrinsically or could also be motivated by information or regulatory instruments. SDP-RC features the highest reduction in consumption (e.g. of meat, heating and cooling demand, light-duty vehicles and air traffic), but again instrument types are not explicit. SDP-MC tends to lie in between SDP-RC and SDP-EI, but assumes the strongest systemic shifts (e.g. achieving highest electrification in energy end use sectors), modelled through a combination of demand- and supply-side measures. Shifts in transport modes could be interpreted as driven by both systemic changes (e.g. improved public transport infrastructure) and/or demand pull changes (e.g. subsidies for public transport), even if this is not explicitly represented in the models. Hence, in the modelled SDPs instruments and interventions with demand pull purpose are a major driver of change (especially in SDP-RC and SDP-EI), but depending on the scenario, interventions with technology push (especially SDP-EI) and systemic (especially SDP-MC) purposes are also present, but are currently not underpinned by explicit instrument types.

4.3. Assessing the SDPs' policy mixes characteristics

The above shows that the modelled SDPs foresee specific instrument mixes for certain intervention areas, even if not all intervention areas are underpinned by specific policy instruments. In the following we look at the static and dynamic characteristics of subsets of these policy mixes, followed by credibility considerations.

4.3.1. Static characteristics: policy coherence, consistency of instruments and comprehensiveness

Policy coherence, including consistency of instruments, is achieved when policies in a mix work in a way that limits trade-offs and enhances synergies between them. The SDP narratives cover almost all SDGs (Kriegler *et al* in preperation), having goals and interventions across a wide range of policy fields. Inevitably, this leads to various interactions between policies not only within but also across sectors. By taking goals across multiple dimensions into account, the quantified SDPs pay attention to these interactions, considering eleven SDGs explicitly (Soergel *et al* 2024). Overall, bans, limits and protection measures were purposefully introduced in the SDPs to better account for the links between forestry, agriculture, biodiversity and energy and to reduce negative external effects of climate change mitigation efforts compared to 'standard' mitigation scenarios (based on SSP 2) (Soergel *et al* 2024, Weindl *et al* 2024). Yet, the link to water remains limited.

Beyond regulatory instruments, trade-offs are also addressed through price adjustment (e.g. tax on bioenergy) and carbon tax revenue recycling as a compensatory instrument to reduce carbon-price induced poverty and inequality. In implementing such interventions, each scenario comes with its own set of challenges. For instance, it is harder to meet biodiversity targets in SDP-EI due to competing interests with land use for economic activities. In SDP-RC, the risk of energy poverty especially in the Global South is mitigated through inequality reduction built into the scenario and efficiency improvements (Kikstra *et al* in review). Nonetheless, while the modelled SDPs have a much higher representation of the interactions between measures within and between sectors than earlier SSP scenarios, still this representation remains limited and, hence, policy coherence cannot be fully ensured.

Comprehensiveness is determined by the degree to which the policy mix addresses all market, system and institutional failures by pulling different levers, covering all three instrument purposes. In the model runs explicit instruments with demand pull purpose prevail, although at the level of interventions all three purposes are covered to some extent with variation between the scenarios, but instruments types are not explicit. This implies that at present, none of the scenarios is fully comprehensive.

4.3.2. Dynamic analysis: smart policy sequencing, creative destruction, innovation, robustness and resilience

In the modelled SDPs, policies are sequenced to a certain degree. Carbon prices are assumed to be introduced at moderate levels in early years and to gradually increase over time. In addition, the REMIND-MAgPIE scenario quantification initially assumes a lower carbon price for world regions with low income. The sequencing furthermore includes creative destruction, replacement of long-standing practices or procedures with better aligned and more innovative or disruptive practices. Examples include the phase-out of coal and the phase-in of hydrogen and CCS or the replacement of diesel cars with electric cars or other transport modes. The models furthermore increase energy efficiency or reduce waste over time. The modelled scenarios also foresee the gradual phase out (REMIND-MAgPIE) or phase down (IMAGE) final energy subsidies. For the phase-in, the narratives determine innovation and how quickly technologies develop; in the modelled scenarios this is mainly driven by the respective carbon prices. While rapid changes and innovations are expected with regard to technologies in SDP-EI, similarly ambitious change and innovations are expected for consumption patterns in SDP-RC. Although all scenarios will need innovation in policy design, the SDP-MC narrative and scenario is in the middle between SDP-EI and SDP-RC and requires the largest involvement from governments and highest degree of policy innovation. In REMIND-MAgPIE adverse effects of carbon prices are mitigated through revenue recycling.

In terms of robustness and resilience, forward-looking models typically cannot consider context changes or unpredictable external shocks that could lead to implementation challenges. While the effects of COVID-19 on the global economy are taken up in the model runs (Koch and Leimbach 2023), the effects of the Russian invasion of Ukraine are not. Nevertheless, a certain level of robustness and resilience are built into the model implementation. For instance, some parameters set in the model might have similar effects (e.g. reduced demand as scenario assumptions versus price effects), hence building robustness through redundancy. The use of revenue redistribution to address inequalities in the SDPs builds resilience through safety nets and reduces poverty and inequality.

4.3.3. Credibility

To be credible, a policy mix needs to be believable and consider the local contexts and various factors influencing its implementation. For the SDPs, models take into account differences in world regions, but do not account for country differences. For instance, in line with historical data a higher floor space per capita is assumed in North America than in Africa in early scenario years, with gradual convergence over time and REMIND-MAgPIE initially differentiates the carbon prices according to income level across world regions. There is also differentiation in acceptability, relevance, and uptake of certain technologies and approaches for the three scenarios, e.g. for hydropower, nuclear and CCS in the IMAGE implementation of SDP-EI.

All three SDP scenarios implicitly assume prevailing peace, rule of law and high institutional quality (government effectiveness, good governance) to enable effective implementation of their ambitious goals (see also Leininger *et al* in review, Soergel *et al* 2021). Factors including political regime type, electoral cycles, commitment of political leadership, state capacities and actors' interests and their interdependencies that may strongly influence implementation are not represented. In that sense, implementation of the relatively high carbon price, even if lower than in SSP climate scenarios due to other interventions, can be expected to be challenging. Empirical studies on emissions trading schemes (ETS) show how they are often watered down due to political economy factors and thus impacts remain limited (e.g. Wang *et al* (2022) for California's ETS). Moreover, not all policy costs are taken into account, with the models focussing mainly on the costs of climate policy defined as percent of GDP or investment requirements for the energy system. REMIND-MAgPIE considers revenue recycling from the carbon tax, whereas IMAGE does not. Overall, while the modelled SDPs have certain credibility in terms of regional differentiation, their implicit governance assumptions remain extremely optimistic.

5. Discussion and conclusion

As ambitious, coherent, comprehensive and credible policy mixes and synergistic combinations of governance modes are needed to achieve the 17 SDGs simultaneously, we drew on different strands of literature on policy mixes to analyse policy-mix representation in target-seeking SDP scenarios. Thus, we initiated an interdisciplinary conversation between the literatures on scenario modelling and policy, governance and transitions studies. In a first step, we analysed to what extent governance modes and policy instruments and purposes are explicitly or implicitly represented in quantified SDPs. While the narratives each assume dominance of a different governance mode for the three SDPs (SDP-EI markets, SDP-RC networks, SDP-MC hierarchies), modelled SDPs explicitly and implicitly represent markets and hierarchies as drivers of model outcomes. While societal networks are not represented, they can be expected to play a larger or lesser role depending on the scenario. Economic instruments, most prominently an increasing global carbon price that varies across SDPs, are explicitly represented in the models. In addition, the quantified SDPs foresee several bans, limits and protection measures that can be understood to mimic regulatory instruments to increase policy coherence across sectors. Beyond this, models rely on various supply- and demand-side interventions that could be triggered by different policy instruments, depending on the underlying narrative. As such, the modelled SDPs can be interpreted as alternative policy mixes for sustainability transformations, even if they are only partially spelled out so far. The SDPs hence better account for policy mixes than earlier climate-focussed IAM scenarios, as Keppo *et al* (2021) demand.

In a second step, we applied the conceptual literature on policy mix characteristics (Rogge and Reichardt 2016, Howlett 2019, Kern *et al* 2019) to the quantified SDPs. By analysing policy mixes in quantified scenarios, we contribute to an open research question in policy studies how the characteristics and the effects of policy mixes can be studied (Capano and Howlett 2020). We find that from a static perspective, the SDPs ensure a higher level of policy coherence and consistency of instruments across sectors than earlier climate-oriented SSP scenarios through mimicking regulatory instruments, price adjustments and carbon tax revenue recycling. The comprehensiveness of the modelled scenarios is somewhat limited, as explicit instruments with demand pull purpose prevail. In addition, depending on the scenario, additional interventions with either technology push, demand pull or systemic purposes come into play. From a dynamic perspective, SDPs provide explicit and implicit assumptions on policy sequencing including creative destruction and the phasing in of new technologies. Robustness is to some degree addressed through redundancy of measures and resilience to external shocks through safety nets, such as revenue recycling. Credibility of policy mixes is attained to a very basic degree through consideration of differences among world regions. However, given their high ambition, the SDPs implicitly assume rule of law and high institutional quality, prevailing peace as well as high political and social ambition to enable effective implementation. The scenarios also do not account for political economy considerations and financial constraints in implementation. In that sense, their credibility remains limited.

Overall, the quantified SDPs confirm the relevance of policy mixes and assumptions on required static and dynamic policy mix characteristics for sustainability transformations. By examining the SDPs against these policy-mix characteristics, the paper also contributes to the modelling literature by providing an initial pathway appraisal and suggests that future scenarios should further improve along these characteristics.

This paper uncovered IAM model assumptions on policy mixes, which are sometimes viewed as a black-box by non-modellers. As such, it aimed at providing guidance on what needs to be considered by policymakers when seeking to realise the SDPs. We also provided some examples on how interventions in the scenarios not specified by policy instruments could be underpinned by policy instruments depending on the scenario, even if a comprehensive analysis of policy options for all interventions was beyond the scope of this paper. Despite the examples provided, it remains open whether it is possible to induce all innovations or behavioural changes needed for sustainability transformations through policy. This points to the potential limits of steering sustainability transformations through policy mixes alone, and calls for better understanding of societal change mechanisms beyond policy factors.

The above points to the following interdisciplinary research avenues. For social scientists: relate the SDPs to empirical research on policy mixes and behavioural change to get a better understanding of the conditions under which change occurs. For modellers and social scientists: jointly further improve the representation of (1) policy instrument types and purposes, policy mixes and their interactions, and (2) underlying socio-political dimensions (Leininger *et al* in review) in the models, for instance by considering how institutional capacity influences policy sequencing. This requires (i) a more granular representation of sub-systems, (ii) endogenising more socio-political elements, and (iii) exploring further opportunities to link to other types of models.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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