Integrating Global Climate Change Mitigation Goals with Other Sustainability Objectives: A Synthesis

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welfare-theoretical framework, multiple objectives, cobenefits, air quality, energy security, energy efficiency, energy demand reduction

Abstract

Achieving a truly sustainable energy transition requires progress across multiple dimensions beyond climate change mitigation goals. This article reviews and synthesizes results from disparate strands of literature on the coeffects of mitigation to inform climate policy choices at different governance levels. The literature documents many potential cobenefits of mitigation for nonclimate objectives, such as human health and energy security, but little is known about their overall welfare implications. Integrated model studies highlight that climate policies as part of well-designed policy packages reduce the overall cost of achieving multiple sustainability objectives. The incommensurability and uncertainties around the quantification of coeffects become, however, increasingly pervasive the more the perspective shifts from sectoral and local to economy wide and global, the more objectives are analyzed, and the more the results are expressed in economic rather than nonmonetary terms. Different strings of evidence highlight the role and importance of energy demand reductions for realizing synergies across multiple sustainability objectives.

Contents

1. INTRODUCTION

A large body of literature has looked at the challenge of meeting stringent climate targets (1–6). However, many argue that stringent climate change mitigation goals are a necessary but insufficient condition for a sustainable energy transition (7–9). Other key sustainability objectives include improved air quality and health, the provision of affordable energy services for all, energy and food security, as well as minimizing energy-related land and water use and biodiversity loss. Mitigation efforts should hence be assessed in a multiobjective framework (8–12), which would need to consider the energy transition as a multilevel governance challenge. On the one hand, mitigation is a global commons problem that warrants a coordinated global response (13, 14). In fact, the integrated model literature has shown that achieving particular mitigation goals, such as the 2°C target, is most cost-effective if approached from a global perspective and results in high long-term global benefits at considerable short-term costs (15, 16). On the other hand, most climate policies are increasingly formulated at national and even subnational levels, where many of the nonclimate objectives are often more salient as policy drivers (17–19). Because cobenefits of mitigation hold the prospect of helping achieve some of these other objectives and reducing the short-term costs of climate policies that accrue on the local/national level, the concept has recently attracted increasing attention. Hence, tailored information on the interactions of mitigation and other sustainability objectives is required to guide choices within a multilevel governance framework ranging from the global to the national and subnational levels.

The *Working Group III Contribution to the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report* (WGIII AR5) (20), based on the assessment of global integrated model results, highlights that there is no single preferred mitigation pathway for cost-effectively meeting any specific temperature goal. Instead, it indicates that there is flexibility in how a particular mitigation goal can be achieved: The timing of greenhouse gas (GHG) emissions reductions, the choice of particular sets of low-carbon energy supply technologies and their upscaling requirements, etc., can substantially differ across scenarios, both globally and locally (1). Policy makers can increase the level of flexibility by enacting policies that help reduce energy demand (5, 21) and can harness this flexibility by choosing climate policies according to national/local circumstances and preferences. These include the levels of socioeconomic and technological development, distributional aspects, risk perceptions, and priority settings for nonclimate objectives (7, 19, 22).

Although there is a wealth of relevant literature on synergies and trade-offs across mitigation and nonclimate objectives, evidence remains scattered across different sectoral studies, different research communities, and different scales of analysis. This makes it generally inaccessible for decision making. As with the rapid expansion of literature in climate science in general, there is not enough meaningful interpretation of the sum of the individual sets of results (23; see also 24–26 for bioenergy research). Indeed, the benefits of integrating sectoral evidence with evidence from scenario studies have been highlighted in recent reviews (24, 27–30). Such an integrated perspective is highly relevant for decision making because it advances the understanding of the practical implications of alternative climate policy choices for other human and policy dimensions (8–10, 31).

In this article, we try to connect relevant strings of evidence (scattered across many different strands of literature and different scales of analysis) on the interactions between mitigation and other sustainability objectives. By doing so, we generate new insights and identify robust evidence for policy makers—even for those locations for which no scientific evidence is directly available. This article focuses on a global perspective, aiming to provide insights on the interactions of mitigation and nonclimate objectives relevant for understanding the global energy transition challenges.[1] The WGIII AR5 has already made important progress in assessing this broad body

Mitigation (of climate change): reducing the sources or enhancing the sinks of GHGs; or reducing other substances that contribute directly or indirectly to limiting climate change

Cobenefits: the potential positive effects of a policy aimed at one objective on other objectives, without evaluating social welfare implications

WGIII AR5: Working Group III Contribution to the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report

Mitigation pathway: the trajectory to meet a given mitigation goal that implies a set of economic, technological, and behavioral changes

Greenhouse gas (GHG): gaseous constituents of the atmosphere (natural and anthropogenic), which absorb and emit radiation at specific wavelengths emitted, e.g., by Earth's surface

[1]In practice, the stated rationale of a particular climate policy at the national or local level may not be restricted to mitigation and may be different in varied contexts. In fact, mitigation is often considered the cobenefit of other policies primarily aimed at environmental, health, and development issues (32). The aim of this article is, however, less to illuminate the different drivers of implementing mitigation-related policies at the national or local level but instead to synthesize existing evidence on

Sustainable development (SD): development that meets the needs of the present without compromising the ability of future generations to meet their own needs

Adverse side effects: the potential negative effects of a policy aimed at one objective on other objectives, without evaluating social welfare implications

of literature by (*a*) providing both a social welfare and a sustainable development (SD) framework for climate policies in a multiobjective context, (*b*) assessing the literature on coeffects of mitigation measures in different sectors, and (*c*) assessing the integrated model literature on coeffects of mitigation pathways on a global scale. It has, however, only provided a limited synthesis, which is divided across several chapters of the report. This has hindered a comprehensive view with more far-reaching insights on this important topic. We further condense and expand the synthesis of the material by (*a*) presenting the different WGIII AR5 chapters' results at a single glance (see the tables in Sections 3 and 4.1 below), (*b*) analyzing the challenges of quantitative aggregation of coeffects, particularly on a global scale, (*c*) presenting a way forward to usefully draw on existing strings of evidence, (*d*) discussing the high-level insights gained, and (*e*) pointing to a promising research agenda for multiobjective literature and its synthesis.

To that end, Section 2 provides a welfare-theoretical framework that serves as an organizational device for the review and condensation of sectoral research results in Section 3 and of integrated model literature results in Section 4. These sections discuss the various aspects focused on by different communities in their analysis of the interactions of mitigation and multiple other sustainability objectives, pointing to their respective strengths as well as the caveats for quantitative synthesis. Section 4.3 critically discusses the extent to which integrated models are actually able to assess changes in welfare, and Section 5 suggests one possible way forward to make multiobjective implications of climate policy choices more transparent by drawing on the respective strengths of these different communities. Although this approach does not eradicate the incommensurability in the aggregation of various coeffects, particularly on a global scale, it deals with the uncertainties of different sets of results in a more transparent way. It also makes them more accessible to decision makers who would like to understand how to maximize synergies and minimize trade-offs across multiple sustainability objectives.

2. A CONCEPTUAL FRAMEWORK FOR ASSESSING THE COEFFECTS OF MITIGATION

Despite a long-standing interest in the coeffects of mitigation (see, e.g., 33), there is no commonly agreed upon terminology. For example, positive (negative) coeffects are referred to in the literature as cobenefits or ancillary benefits (co-costs, ancillary costs, adverse side effects or trade-offs), but these terms have been defined differently across studies (see 12 for a review). This is largely because the same terms have been used to describe a range of effects from different methodological approaches. The sidebar A Conceptual Welfare-Theoretic Framework for Assessing the Coeffects of Mitigation introduces a conceptual welfare-theoretical framework. We use this framework as a device for structuring our literature review and condensation of insights from different strands of literature.

We classify the literature into three main strands based on this framework. **Figure 1** provides an overview and relates the strands to each other. Most importantly, it highlights that the system boundaries of the strands are very different. System boundary expansion from strand 1 to 3 is paved with complexities and practical problems, which explains the increasingly thin literature base.

Literature strand 1 (from climate change mitigation measures to multiple objectives; see I in **Figure 1**) links mitigation measures, defined here as "technologies, processes and practices that contribute to mitigation" (37, p. 1266), to other sustainability objectives z_i ($i = 1, \ldots, m$). In

the global implications for multiple sustainability objectives and social welfare if governments embark on alternative global mitigation pathways.

A CONCEPTUAL WELFARE-THEORETIC FRAMEWORK FOR ASSESSING THE COEFFECTS OF MITIGATION

Suppose social welfare W can be written as a function of different objectives z_i ($i = 1, \ldots, m$); the attainment of each of those objectives is influenced by the deployment of a number of technological or other measures m_k ($k = 1, \ldots, n$), which, in turn, are influenced by the implementation of a number of policies, p_l ($l = 1, \ldots, o$). Now consider a marginal change dp_l in one or more policies. Building on the conceptual framework presented by Kolstad et al. (34), but highlighting the important role of the broad set of measures through which policies often impact objectives, the net effect on social welfare effect is given by Equation 1.[2]

$$dW = \sum_{i=1}^{m} \sum_{k=1}^{n} \sum_{l=1}^{o} \frac{\partial W}{\partial z_i} \frac{\partial z_i}{\partial m_k} \frac{\partial m_k}{\partial p_l} dp_l. \qquad 1.$$

Based on these considerations, we define cobenefits (or adverse side effects) as the potential positive (or negative) effects of a policy p_l aimed at one objective on other objectives ($\frac{\partial z_i}{\partial m_k} \frac{\partial m_k}{\partial p_l}$ for $l \neq i$), without evaluating the implications for social welfare (not multiplied by $\partial W / \partial z_i$, i.e., the value different individuals or society as a whole attach to the coeffect). This differentiation between the nonmonetary effect on a particular objective and the associated social welfare effect is important because the overall magnitude is determined by the two effects in combination, which may also work in different directions (see Section 4.3). Moreover, coeffects are often reported in nonmonetary or even qualitative terms only because they are challenging to measure, quantify, and monetize because of a variety of practical obstacles, such as data availability (see, e.g., 12, 35, 36).

particular, it characterizes these mitigation measures in terms of their multiple cobenefits and adverse side effects on nonclimate objectives (see Section 3), mostly in the context of specific sectors/applications and locations. Other coeffects accrue to stakeholders outside the sector/location (upstream, downstream, or downwind). Such evidence can inform the technological choices of national and local policy makers by highlighting the potential coeffects of mitigation measures for other objectives. This task remains challenging, however, because the wealth of evidence is scattered across multiple research communities and studies, each dealing with specific aspects, sectors, locations, and sometimes policies, but neglecting cross sectoral and cross regional interactions of policies, technology choices, and the associated implications for social welfare.

Literature strand 2 (from climate policies to mitigation measures to multiple objectives, see II in **Figure 1**) analyzes the implications of a stylized global climate policy (i.e., a global mitigation goal) for other sustainability objectives via the deployment of globally cost-effective portfolios of mitigation measures and the resulting macroeconomic mitigation costs. The analysis has been largely limited to the coeffects of mitigation on one sustainability objective at a time—and in some cases vice versa (see Section 4.1). This body of research can be an important source of evidence for policy makers, potentially changing the incentive structure for global mitigation efforts if near-term benefits for other objectives (e.g., local air quality) are more explicitly taken into account (36, 38–44). This strand focuses, however, on the coeffects of mitigation pathways in nonmonetary

[2]Please note that spatial, temporal and distributional dimensions have been omitted from Equation 1, although they are discussed where relevant. A discussion of changing governance conditions is beyond the scope of this article.

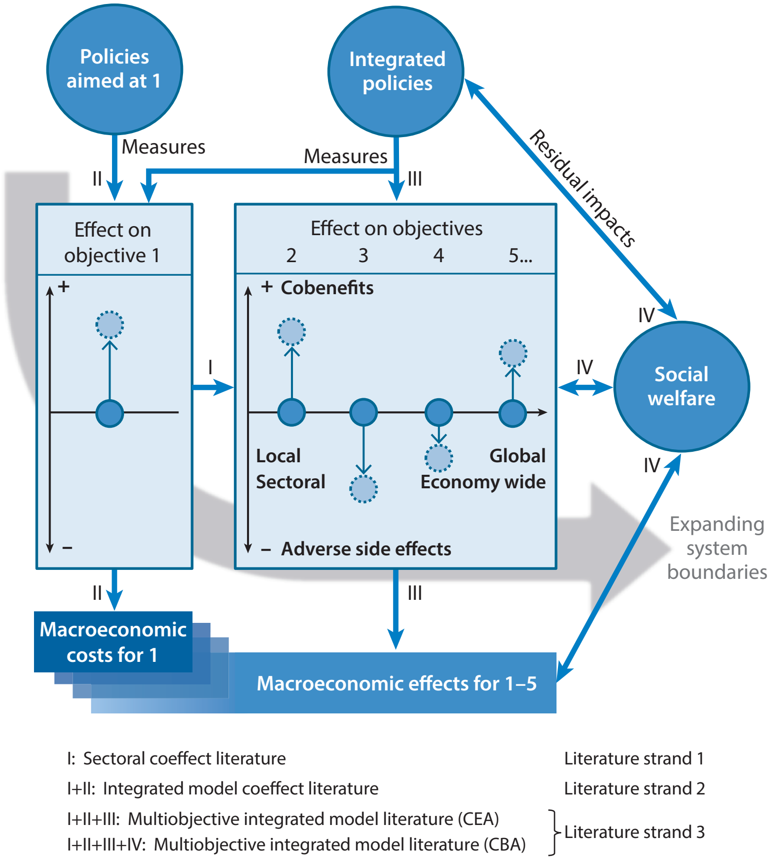

Figure 1

Schematic overview of important terms and concepts linked to the different literature strands on the interactions of mitigation, other objectives, and social welfare, following Equation 1. Abbreviations: CBA, cost-benefit analysis; CEA, cost-effectiveness analysis.

terms and neither explicitly considers interactions of climate and nonclimate policies nor the resulting macroeconomic effects (beyond aggregate mitigation costs).[3]

Literature strand 3 (from integrated policies to measures to objectives to welfare; see III and IV in **Figure 1**) adds another step by not only considering how integrated policies (i.e., climate and nonclimate) through different measures contribute to multiple objectives but also analyses the policies' respective macroeconomic effects. To analyze the aggregated importance of the synergies and trade-offs between multiple objectives resulting from alternative policy packages on a global scale, different integrated models have sought to extend their system boundaries to embrace a multiobjective perspective. Because welfare effects are only significant in second-best environments (i.e., if there are multiple externalities that are not fully internalized; see Section 4.3), the existing studies look at a smaller set of objectives than the other literature strands to deal with

[3]Barker et al. (45) reviews studies that apply computable general equilibrium models for evaluating the welfare impacts of climate vis-à-vis nonclimate policies, but with a focus on specific regions and policies in the short to medium term (e.g., Chile and China). They are thus not suitable for drawing lessons for a global scale and longer time horizons.

rising complexity (see Section 4.2). Although one modeling approach compares many different future mitigation scenarios based on various combinations of policies to achieve different levels of multiple energy policy objectives [cost-effectiveness analysis (CEA), III in **Figure 1**], another modeling approach equalizes marginal costs (including residual impacts) and benefits (including avoided impacts) to determine socially optimal policy stringencies [cost-benefit analysis (CBA), IV in **Figure 1**]. Owing to major conceptual challenges in integrating several objectives in a decision framework, this evidence base is still in its infancy (7, 10, 34, 46, 47).

Cost-effectiveness analysis (CEA): a tool based on constrained optimization for comparing policies designed to meet a prespecified target

Cost-benefit analysis (CBA): monetary measurement of all negative and positive effects associated with a given policy

3. SECTORAL RESEARCH RESULTS ON THE COEFFECTS OF MITIGATION MEASURES

This section provides a qualitative meta-analysis of the many existing studies on mitigation coeffects from the sector-specific research assessed in the WGIII AR5. Our goal is to expand its high-level findings and the associated implications for multiobjective decision making. The section also identifies the most important caveats that are associated with the quantification and global aggregation of coeffects—often referring to literature on air pollution because it is the most thoroughly researched coeffect (12, 36, 41).

The qualitative meta-analysis in **Figure 2** on the potential coeffects of sectoral mitigation measures for a wide range of sustainability objectives builds on several hundred studies that were published after the WGIII AR4 (48) and assessed in the different sector chapters of the WGIII AR5 (20). Although the underlying studies were often conducted for locally specific circumstances, the potential for such effects in one location often implies that they are possible or even likely in other locations with similar circumstances. Some studies are able to draw on existing data for some of the sectoral measures (particularly bioenergy), but many studies on coeffects are forward-looking because many mitigation measures are not yet implemented for various reasons.

Owing to space constraints, **Figure 2** focuses on the effects for which a considerable number of studies exist. To facilitate a structured overview, the mitigation measures on the demand side and the associated coeffects are classified into three broad strategies: (*a*) fuel switching to low-carbon energy carriers/fuels, (*b*) technical energy-efficiency improvements, and (*c*) energy demand reduction through other means (e.g., behavioral/structural changes)—largely following Edenhofer et al. (11, table TS.3). The coeffects for the different sustainability objectives are classified along the three SD pillars—economic, social, and environmental [see Fleurbaey et al. (7) on the relation between multiple objectives and SD]. Although some objectives can be regarded as ultimate end points (e.g., health), others are intermediate end points (e.g., water pollution), following the availability of literature on the respective coeffects.

The extent to which any of these effects will eventually materialize also depends on other factors. These include the scale, scope, and pace of implementation of the mitigation measures, which are not discussed in detail here. In the **Supplemental Material**, the reader can find condensed information on the coeffects from **Supplemental Table 1** (follow the **Supplemental Material link** from the Annual Reviews home page at **http://www.annualreviews.org**) in the context of the appropriate sector. Two broad messages that are globally relevant for decision making can be derived from this meta-analysis:

Supplemental Material

1. For mitigation measures on the demand side, the potential cobenefits outweigh the risks; on the supply-side, the balance depends to a larger degree on the specific measure (1). This implies that efficiency and other measures to reduce sectoral energy demand are robust strategies across multiple objectives but that the overall coeffects of fuel switching are not as clear-cut (see further below in this section). In these cases, the number of potential positive versus negative effects is not necessarily a good indication for the net effect on welfare

Sector	Sectoral mitigation measures		Economic: Energy security	Economic: Sectoral productivity	Economic: Local/sectoral employment	Social: Reduced health impact	Social: Thermal comfort, work conditions	Social: Safety/disaster resilience	Environmental: Reduced ecosystem impact	Environmental: Reduced water use/pollution	Environmental: Reduced land use	Other objectives
Low-carbon energy supply	Nuclear	Replacing coal	↑[a]		↑	↑ ↓		↓	↑↓			Nuclear proliferation, nuclear waste
	Renewable (excluding bioenergy)	Replacing coal	↑		↑	↑			↑↓	↑↓		Energy access, particularly off-grid; Increased resource mining
	Coal with CCS	Replacing coal			↑↓	↓		↓	↓	↓		Long-term monitoring of CO_2
	BECCS (excluding coeffects of bioenergy)	Replacing coal				↓		↓	↓	↓		Long-term monitoring of CO_2
	Bioenergy[b]		↑		↑↓	↑↓			↓[c]	↓	↓	Food security and equity in land tenure
Transport	Fuel switching		↑			↑[d]		↓	↑ ↓			Technological spillovers to developing countries
	Technical energy efficiency		↑			↑		↑	↑			
	Urban form/modal shift[e]		↑	↑	↑ ↓	↑		↑	↑		↑	Equitable mobility access
	Energy demand reduction via other means		↑	↑		↑			↑↓		↑	Reduced urban congestion
Buildings	Fuel switching		↑		↑	↑			↑			Reduced fuel poverty
	Technical energy efficiency[f]		↑	↑	↑	↑↓	↑	↑	↑	↑		Reduced fuel poverty
	Energy demand reduction via other means[g]		↑			↑			↑			
Industry	Fuel switching (including CCS)			↑		↑	↑		↑	↑		Increased competitiveness
	Technical energy efficiency		↑	↑	↑	↑	↑	↑	↑	↑		Technological spillovers
	Material efficiency				↑	↑		↑	↑			Reduced resource mining

Figure 2

The wealth of evidence from sectoral research on the potential coeffects of sectoral mitigation measures on additional sustainability objectives, described in part by the following colors and symbols: green arrows/text, potential cobenefits; orange arrows/text, potential adverse side effects; smaller arrows, small-scale effects by comparison; blank cell, the effect is either unlikely or is not reported in the literature; gray-shaded cells, potential effects also possible outside the location of implementation. **Figure 2** is based on a qualitative meta-analysis of the sectoral literature on nonmonetary indicators for coeffects in the WGIII AR5 sector chapters on energy supply (21), the transport sector (54), the buildings sector (52), the industry sector (147), and bioenergy (102). Abbreviations: BECCS, bioenergy and CCS, i.e. the application of CCS technology to bioenergy conversion processes; CCS, carbon dioxide capture and storage.
[a]Relates to reduced exposure to fuel price volatility; the concentration of the nuclear supply chain may, however, lead to long-term stresses (148).
[b]The coeffects of bioenergy heavily depend on the development context and the scale of the intervention. Other agriculture, forestry and other land-use (AFOLU) measures are not included in this table because they are not directly related to energy transition (see 26, 102, and 109 for an overview).
[c]This is mainly valid for large-scale monocultures.
[d]Excluding diesel.
[e]Land-use planning can create the underlying conditions for colocated higher employment and residential densities that are necessary to support the use of public transport (see 18).
[f]Including efficient equipment as well as insulation interventions.
[g]Based mainly on behavioral changes.

because some large effects in terms of the change of nonmonetary indicators may have very small welfare effects—and vice versa (see Section 4.3).

2. Multiobjective decision making on climate change mitigation can build on a wealth of evidence of the different coeffects on many policy-relevant objectives. In fact, the scientific literature covers the coeffects of most sectoral mitigation measures for energy security and reduced health and ecosystem impacts. This is, however, not the case for all objectives: Some effects seem to be rather idiosyncratic to specific (groups of) measures, as shown in the last column of **Figure 2**, highlighting the question of how to compare these different effects. If no arrow is shown, this can imply either that an effect is unlikely to materialize or that no scientific literature is (as yet) available.

It is, however, difficult to gain more than qualitative insights for policy making in one location if the quantitative evidence is based on locally specific circumstances, policies, and assumptions from another location. For example, the net effect of fuel switching on other objectives depends on the extent to which the benefits of switching away from high-carbon energy carriers dominate the context-specific balance of coeffects arising from the increased supply of low-carbon energy carriers. The net effect also depends on how individual measures are implemented, affecting the degree to which each unit of low-carbon energy actually replaces one unit of high-carbon energy (49). Many studies discuss the example of biofuel deployment and its effect on total global fuel consumption, but they do not agree on its quantitative importance (e.g., 50, 51). In the same way, energy-efficiency measures in the energy demand sectors may not necessarily lead to the possible energy demand reductions because rebound effects can occur. These also differ across different locations (52, 53). In fact, a multitude of changes (e.g., in climate and nonclimate policies, energy prices, and energy supply and demand resulting from technological and behavioral changes) makes any comprehensive analysis highly complex, and estimations of these rebound effects vary widely (21, 54, 55). **Figure 2** addresses this challenge of context-specific circumstances by assuming, in the first part of the table, that each unit of low-carbon energy supply replaces one unit of coal (instead of a locally specific energy mix). This specification is required to establish a baseline against which the lower-carbon energy supply technologies can be evaluated with respect to other objectives.

This implies that any quantifiable results reported in the literature depend largely on the system boundaries chosen for the analysis of individual studies. In contrast to the cross regional, cross sectoral mitigation perspective adopted by the integrated models discussed in Sections 4 and 5, sectoral research on coeffects often focuses on a particular location/country. This allows the research to take into account locally specific detail, which in turn is useful for informing local/national policy priorities and processes, but this level of detail is less useful as a basis for generalized results. The diverging foci can partly be explained by the fact that mitigation effects are independent of the location of GHG emission reductions, whereas many of the coeffects are most salient as policy drivers at the local scale (19, 41, 56).[4]

Moving beyond technological aspects, the empirical projections for coeffects of individual sectoral studies also depend on explicit or implicit assumptions on the effectiveness of existing or planned nonclimate policies at the national and local levels that target the nonclimate objectives directly, i.e., the projected baseline developments in the absence of climate policies (35, 43, 55, 60, 61). For example, the effects of mitigation measures on air pollution usually differ between wealthier and poorer countries; there are more stringent air quality policies in richer places and,

[4]The most notable exceptions are emissions of non-GHG air pollutants, which are reduced along with GHG emissions reductions when fossil-fuel combustion is avoided. The analysis of many air pollutants also draws on regional and global models (see, e.g., 43, 57–59) because the impacts are not confined to the location of emission. See section 4.1 for a discussion of their climate effects.

hence, a lower base of pollutants squeezing the potential health gains (35, 41, 57, 59, 62, 63). The extent to which coeffects materialize also depends on geographical characteristics—even within an individual country where differences can arise, for example, between rural and urban environments. Socioeconomic circumstances that cannot be shaped by policies, at least in the near to medium term, such as different indoor/outdoor activity patterns and the concentration of population, can also impact the associated exposure to air pollution (29, 35, 45, 64).

Despite these caveats in quantifying the coeffects of mitigation policies in nonmonetary terms, many researchers have gone one step further by monetizing them. They build on economic valuation techniques that are used in research fields such as health and environmental economics (12, 34, 64). Some of the studies on monetized health cobenefits through air quality improvements, for example, cover a wide range of estimates: $2–840 per ton of CO_2 saved (see 41 for an overview, 59 for the upper estimates). This is due to, inter alia, consideration of diverse locations, mitigation and air quality policies, pollutants, impact channels, economic sectors, time horizons, and valuation techniques (see, e.g., 35, 41, 45, 55, 65).

In conclusion, many of the qualitative results for the various coeffects of mitigation measures derived for a single location are critical for decision making in that location. They can also be helpful for decision makers elsewhere to gain an overview of the potential effects of the many available sectoral mitigation measures. At the same time, any quantitative aggregation of sectoral research results on coeffects, particularly at a global scale, beyond the qualitative meta-analysis presented above, remains challenging owing to the incommensurability in results across effects, sectors, and locations—despite the vast amount of literature that has recently developed. Such an aggregation is, however, a prerequisite for a detailed understanding of the importance of global-scale synergies and trade-offs across mitigation and the many other global-scale sustainability objectives. The next section discusses quantitative results from integrated models on these interactions, building on a unified framework of analysis with respect to future global climate policy and a number of harmonized exogenous key parameters across models (see **Supplemental Material Section 1**). This makes their results at the global level more comparable and accessible to decision makers, but it is at the expense of the rich sectoral details presented above.

Supplemental Material

4. INTEGRATED MODEL RESULTS ON THE INTERACTIONS OF MULITPLE SUSTAINABILITY OBJECTIVES

The results of the interactions of mitigation and other sustainability objectives from integrated model studies assessed in the WGIII AR5 (1) are further condensed and discussed in this section to expand on the high-level findings and the associated implications for multiobjective decision making. One important advantage of this literature is that the deployment projections capture cross regional and cross sectoral interactions of mitigation measures.[5] On the basis of methodological insights in analyzing the coeffects on specific objectives from the sectoral literature (see Section 3), the integrated models have expanded their system boundaries to analyze the interactions of global mitigation goals and additional objectives in one research setup, such as air quality and its health implications, energy security, energy access, as well as minimizing energy-related biodiversity loss and water and land use. Although the majority of these studies focus on the coeffects of mitigation pathways on one other objective, or vice versa, in nonmonetary terms (see Section 4.1), a few recent analyses have looked at the interactions of integrated policies for multiple objectives, in some cases

[5]To keep model complexity manageable, however, this strand of literature typically projects the effects of stylized policies rather than considering detailed policy instruments. It ignores the potential interactions between different mitigation policy instruments on different governance levels (19, 66).

Direction of analysis between objectives			Indicators used most prominently	Direction of coeffects	Scale of coeffects	Key determinants for the scale of the coeffects	References
Climate change mitigation	→	Air quality and health	SO_2, NO_x, $PM_{2.5}$, Hg emissions or concentrations	↓	2030: up to 50/35/30/22% reductions	Stringency of current/ planned air pollution legislation, ratio of abated warming versus cooling air pollutants	8, 38, 43, 58, 63, 69–72, 75, 120
	←		Midterm global temperature change	↓↑	2030: fraction of 1°C in both directions (effect low after 2050)		
	→	Energy security	Fuel diversity of electricity	↑	2050: 13–36% increase	Energy resource endowment, type of policies pursued, energy supply restrictions and current and future usage	8, 78, 80, 81, 83, 85, 87, 95
	→		Import dependence	↑↓	2050: 10–70% decrease[a]		
	→		Cumulative oil extraction	↓	2050: 2–36% decrease		
	←		GHG emissions	↑	Higher CO_2 emissions versus baseline		
	→	Energy access[b]	People with modern energy access, GJ per capita	↑↓	Unclear net effect (off-grid RE access versus higher energy prices)	Type of fuel used by the poor and policies to support switch to modern energy services	8, 43, 67, 96–98, 100
	←		GHG and SLCP emissions	↑↓	Unclear net effect (more GHGs/less SLCPs)		
	→	Biodiversity loss	Loss in MSA	↓↑	2050: 50% decrease of MSA loss possible (direct and coeffect)	Land-use policies and policies for re/afforestation and bioenergy	67
	←		CO_2 emissions from land use	↓	2050: lower CO_2 emissions	Ecosystems protection policies	
	→	Land-use impact	Million hectares in global land-use change	↑	Higher land-use change versus baseline (high variance across models)	Land-use policies, policies for re/afforestation and bioenergy, soil quality, yield growth	103–105, 110, 121, 149–152
	→	Water-use impact	Number of people in severely water-stressed regions	↓↑	2050: -8–3% (most studies: small reduction) (direct and coeffect)	Implementation practice of water-intensive mitigation options (e.g., bioenergy, afforestation)	67, 114, 115, 122, 153

Figure 3

Overview of integrated model literature results on interactions of mitigation and other sustainability objectives on a global scale as reviewed in Clarke et al. (1, sections 6.3.5 and 6.6), described in part by the following colors and symbols: green arrows, potential cobenefits; orange arrows, potential adverse side effects; smaller arrows, small-scale effects by comparison; gray-shaded cells, research that analyzed the coeffects of pursuing sustainability objectives on mitigation goals. Studies that looked at integrated policies for achieving multiple objectives are discussed in Section 4.2, but their results are also included in this figure. Abbreviations: CO_2, carbon dioxide; GHG, greenhouse gas; GJ, gigajoule; Hg, mercury; MSA, mean species abundance; NO_x, oxides of nitrogen; $PM_{2.5}$, particulate matter 2.5 micrometers in diameter or smaller; SLCP, short-lived climate pollutant; SO_2, sulfur dioxide.
[a]Interregional energy trade is used in the underlying studies as a global proxy for regional import dependence.
[b]Energy access here refers to basic needs for clean, reliable, and affordable energy services and should not be confused with the increased demand for energy services that, at least historically, has been driven by broader economic growth (1).

even taking welfare effects into account (see Section 4.2). A thorough analysis of such welfare effects with numerical models requires a consistent formulation of policy and counterfactual baseline scenarios. Section 4.3 critically discusses these issues as well as the associated cost metrics used in integrated models to convey information on macroeconomic and welfare impacts.

4.1. Integrated Model Results on the Coeffects of Mitigation Pathways

In the integrated model literature, there is growing attention paid to the interactions of mitigation and nonclimate objectives (8, 67). **Figure 3** offers a condensed overview of those studies looking at (*a*) the coeffects of different mitigation pathways and (*b*) the reverse direction, i.e., the effect on climate change if, for example, air quality policies are pursued (indicated by the arrows in the second column).

An increasing body of literature has explored the linkages between air pollutant and climate policies (see 68 and 69 for a review). These studies indicate significant cobenefits of mitigation for a number of different air pollutants—up to 50/35/30/22% reductions by 2030 of sulfur dioxide (SO_2), nitrogen oxides (NO_x), 2.5-μm particulate matter ($PM_{2.5}$), and mercury (Hg) emissions or concentrations against baseline scenarios, respectively (8, 43, 70, 71).[6] At present, only a limited number of global-scale integrated models are able to analyze these effects in some detail. The current versions of these models typically estimate the physical air pollution cobenefits of technological changes motivated by mitigation activities (63); in some cases, air quality and human health impacts are also calculated (43). However, explicit representations of air pollution control costs are for the most part not included. What some of the scenarios do consider are clearly specified policy packages for air pollution control, finding that the cobenefits of mitigation depend on the stringency of current and planned air pollution legislation (cf. Sections 3 and 4.2) (e.g., 40, 69). Other studies have meanwhile analyzed the reverse mechanism: the impacts of air pollution control measures on the global climate. A key point here is that many of the air pollutants also impact radiative forcing as they form aerosols or act as precursors of aerosols or GHGs. There is, however, great uncertainty in the estimates (38, 63, 72–75). Studies focusing on the cobenefits of air pollution policies for mitigation show that they can potentially reduce net radiative forcing and midterm temperature change by up to 0.2°C by 2030. This can only occur, however, under somewhat debatable assumptions, such as limited or no improvements in the control of air pollutants that cool Earth (e.g., SO_2, NO_x) (58, 69, 75). Current science indicates that such climate benefits decrease with increasing mitigation efforts and, more generally, depend greatly on which air pollutants are reduced and to what extent. This is because emissions of SO_2 and NO_x mask global warming because of their cooling effects, whereas emissions of black carbon (BC) and tropospheric ozone precursors contribute positively to radiative forcing (55, 72). Several studies go further by noting that reductions in short-lived climate pollutants do not buy substantial time for CO_2 emissions reductions but can complement concerted mitigation efforts (69, 76, 77). Air pollution policies that are not focused on the cobenefits for mitigation could even exacerbate global warming (63).

A growing body of literature focuses on the energy security implications of climate change mitigation scenarios. From the perspective of energy sovereignty (or risks arising from foreign actors), most of the literature finds that energy trade and imports decline as a result of mitigation (8, 78–82). The bulk of this coeffect emerges after 2030, however, because in the short term mitigation limits domestic coal deployment, which counterbalances the increase in domestic renewables (83). In addition, the increased sovereignty of major importing countries is likely to result in a drop in energy export revenues for the Middle East, the former Soviet Union, and possibly the United States (84–89).[7] Moreover, geographic diversity of production has been found to increase as fossil fuels are phased out of the system (78, 88). The upside of lower extraction rates is less concern over resource scarcity and the related price volatility (78, 83, 93). The literature also finds that mitigation leads to greater resilience from diversification of energy sources in transport and electricity (8, 78, 80, 83). What the scenario literature on the linkages between energy security and mitigation does not include are, for instance, a broad treatment of the robustness concerns related to systemic failures from discontinuities and shocks (94) and a more systematic analysis

Particulate matter (PM): very small solid particles from solid fuel combustion, which cause adverse health effects and can directly add to radiative forcing

Radiative forcing: the change in the net radiative flux at the tropopause due to a change in an external driver of climate change

Aerosol: a suspension of airborne solid [primary particulate matter (PM)] or liquid particles (secondary PM from gaseous precursors) that may influence climate in several ways

Precursors: atmospheric compounds that have an effect on greenhouse gas or aerosol concentrations regulating their production or destruction rates

Black carbon (BC): an aerosol species mostly formed by incomplete fuel combustion, causing a warming effect by absorbing heat into the atmosphere

Short-lived climate pollutant (SLCP): air pollutant emissions that have a warming influence on climate and a relatively short lifetime in the atmosphere

[6]Because the deployment projections are uncertain with respect to the role of individual measures (even for a particular mitigation goal, such as the 2°C target) and different models show different results (see the **Supplemental Material Section 1**), the ranges for these results are relatively large (see **Supplemental Figure 2** for BC and SO_2 emissions).

[7]Though a few studies argue that if costs of unconventional oil were high enough conventional oil producers may actually benefit from climate policies because this market structure would increase the marginal price of oil (90–92).

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of the climate implications of policies targeted at energy security than has been done previously (40, 95).

The impact of climate policy on energy access depends strongly on how the policy is actually implemented. Although the transition from traditional to modern energy could become somewhat more expensive if GHG emissions were priced universally (96), staged implementation of climate policies or dedicated policy schemes could lead to very different results (67). In least-developed countries with a high potential for off-grid technologies, scenario studies have shown that the deployment of renewable energy can help promote access to clean, reliable, and affordable energy services (97, 98). The impacts of policies promoting energy access on climate change are projected to be very small (67, 99). As energy consumption of the world's poorest is very low and modern energy carriers can be used much more efficiently than traditional ones, studies have shown that there is negligible impact on global CO_2 emissions over baseline levels, even if traditional biomass is completely replaced by fossil fuels (100, 101).[8] Moreover, the use of modern energy also reduces emissions of BC, further reducing the net impact on climate (38, 58, 72).

The interactions between climate policy and biodiversity are complex and beset with increased uncertainty from a lack of knowledge regarding the detailed functioning of complex ecosystems. The impact of climate policy on biodiversity particularly depends on the net impact of avoided climate change (and associated changes in air pollution) and the possible impacts of mitigation measures, such as the use of bioenergy and forestry-related measures (the impact here depends on the specific measure). Van Vuuren & Kok (67) show that unless bioenergy is regulated the negative impacts might, in future decades, dominate the positive ones. In the opposite direction, policies to preserve biodiversity could lead to a reduction of CO_2 emissions from land use if they lead to a larger forest area on a global scale (67). This not only depends on local policies to protect specific ecosystems but also on land-use policies in different areas of the world in general (given the potential impacts on food trade).

The relationships between land use and climate policy are complex as several very uncertain relationships exist, and different policies can have very different impacts. For instance, mitigation scenarios tend to use large levels of bioenergy. Models show that this can significantly influence land use or land tenure as land is needed for bioenergy production, potentially leading to a reduction of natural areas (and associated GHG sinks and/or areas for food production). The exact impact depends on assumptions and modeled impacts on (induced) yield changes, dietary patterns, trade policies, land policy, and other GHG policies. The latter could, for instance, lead to an incentive not to increase (or even decrease) the natural area. At the moment, most integrated models only capture some of these relationships, and the net impact is difficult to assess given the uncertainties involved (24, 27, 29, 67, 102–105).[9] Most studies agree that overall it is important to account for the adverse side effects of large-scale use of afforestation and bioenergy, particularly because of food security and land tenure concerns (see 26, 103, 109–111 for a more in-depth discussion and assessment of many other SD implications).[10] This is why many scenarios in the literature explicitly consider futures with limited supplies of biomass for bioenergy

Traditional biomass: fuelwood, charcoal, agricultural residues, and animal dung used with traditional technologies, e.g., open fires for cooking, rustic kilns, and ovens for small industries

Sink: any process, activity, or mechanism that removes a greenhouse gas (GHG), an aerosol, or a precursor of a GHG or aerosol from the atmosphere

[8]Pachauri et al. (100) argue that achieving universal energy access could even reduce global GHG emissions, assuming that 20% of traditional biomass is unsustainably harvested today and hence adds to current net GHG emissions.

[9]Under the heading of water-land-energy nexus, however, local trade-offs are analyzed by a growing research community (e.g., 106–108).

[10]One recent model intercomparison (the first for agro-economic models) found that the effect of lignocellulosic bioenergy deployment, rising to about 100 EJ by 2050, on food prices is significantly lower (5% higher prices on average across models) than the potential effects induced by climate impacts on crop yields in a high-emission scenario (25% higher prices on average across models) (112). Because these effects are closely related to land-use impacts, they are not separately shown in **Figure 3**.

purposes; although this may lead to higher mitigation costs in total, the SD risks could be lower (113).

Gross domestic product (GDP): the sum of gross value added by all producers in an economy for a given period, normally one year

A few studies have looked at the relationship between climate policy and water use. Mitigation reduces water use for fossil-fuel power plants (114; also see the **Supplemental Material Section 4** on energy supply for the varying effect of deploying different renewable energy technologies) but could increase water use for bioenergy production (115, 116; also see the **Supplemental Material Section 4** on bioenergy). In addition, mitigation influences the precipitation and evaporation changes associated with climate change, but these are very uncertain (117). Given these uncertainties, it is challenging to conclude anything on these net impacts at the moment.

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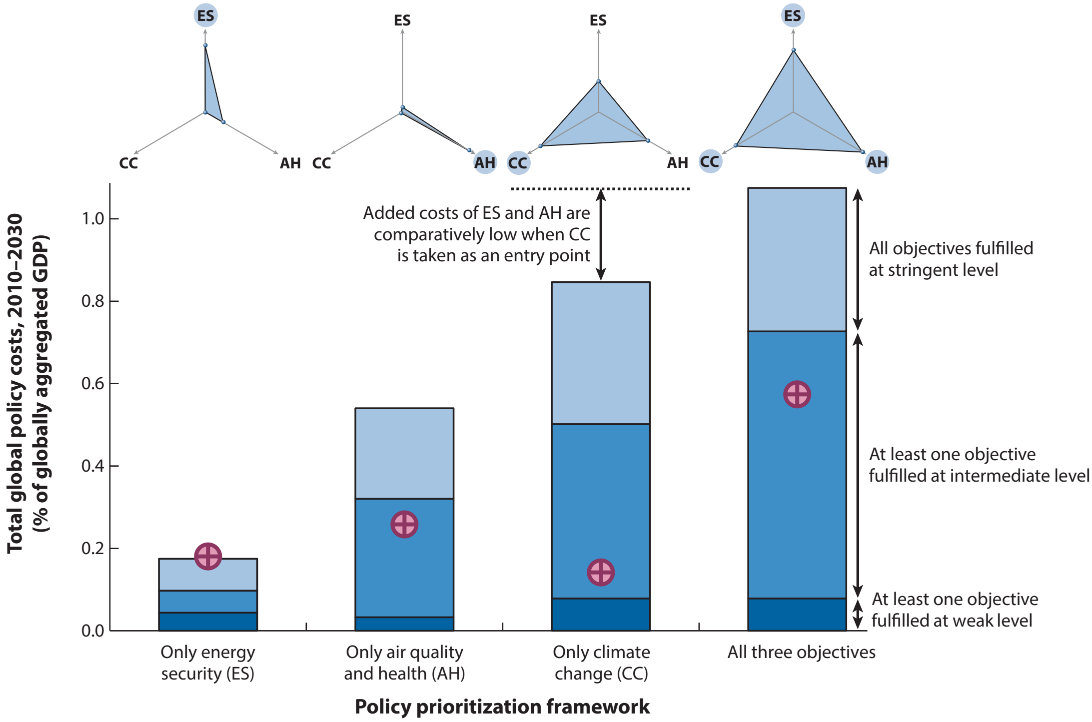
Taken together, the overall evidence on the implications of stringent mitigation goals on other objectives—particularly from multimodel scenario results—is very relevant for multiobjective decision making. For instance, the integrated model literature confirms the insights from more sectoral studies (condensed in a qualitative way in **Figure 2**) that the coeffects of mitigation goals on air quality and energy security via the many sectoral mitigation measures are positive and shows that they are often projected as substantial. At the same time, this synergy is less clear or entirely reversed for the mitigation benefits of policies primarily targeted at air quality or energy security. The majority of the model studies, however, have only explored the coeffects of mitigation on a single additional objective—or vice versa. The next section discusses the recent body of strand 3 literature, which takes a more comprehensive and holistic perspective to explore the interactions of multiple objectives in one study and how to reach them simultaneously with integrated policies.

4.2. Integrated Model Results on Integrated Policies for Multiple Objectives

Some of the modeling teams further broadened the scope of their model tools to analyze integrated policies, which simultaneously achieve multiple objectives: Bollen et al. (95), scenarios developed in the context of the Global Energy Assessment (118; see 8, 40,119), Rao et al. (43), van Vuuren & Kok (67), Rogelj et al. (69), Chuwah et al. (120), Calvin et al. (121), and Akimoto et al. (122).[11] The former two studies quantify key interactions in economic terms on a global scale, which is why they are discussed in more detail in this section. As outlined by Edenhofer et al. (28) and in Section 4.3, analysis of integrated policies, the associated effects on multiple objectives, and the effects on macroeconomic costs or welfare metrics imply consideration of multiple externalities—either explicitly or implicitly.

Bollen et al. (95) developed a set of scenarios using a social welfare optimization approach to assess the costs and benefits (both market and external) of climate, air pollution, and energy security policies, either in isolation or in an integrated way (i.e., a CBA, see the pink circles in **Figure 4**). The GEA scenarios, as pictured in McCollum et al. (119), focus on the same subset of energy policy objectives but instead use a set of normative policy targets (implicitly assuming a second-best environment, i.e., that preexisting externalities are not sufficiently internalized; see Section 4.3) and a large ensemble of scenarios to determine ranges of costs for policy packages of varying stringencies and forms (i.e., a CEA, see **Figure 4** and the table below to explain the three stringency levels for each objective). For both sets of scenarios, **Figure 4** shows global policy costs as a percentage of globally aggregated gross domestic product (GDP) between 2010 and 2030 of pursuing one of the three energy policy objectives in isolation (the three leftmost bars/circles) or

[11]Although the literature on low-carbon society pathways considers multiple sustainability objectives in an integrated way, the models are calibrated to national scales only, which is why they are not discussed here (123–127).



Fulfillment	**Energy security (ES)** Global primary energy trade (EJ/year) 2030	**Air quality and health (AH)** % reduction in global health impacts from baseline 2030	**Climate change mitigation (CC)** CO_2-equivalent (CO_2eq) concentration ranges in 2100
Stringent	<120	>80%	<465 ppm CO_2eq
Intermediate	120–140	25%–80%	465–700 ppm CO_2eq
Weak	>140	<25%	>700 ppm CO_2eq

Figure 4

Costs of achieving three energy policy objectives for different policy prioritization frameworks. For McCollum et al. (119) (*blue bars*), policy costs are derived from an ensemble of >600 scenarios and represent the net financial requirements (cumulative discounted energy-system and pollution-control investments, variable costs, as well as operations and maintenance costs) over and above baseline energy-system development, which itself is estimated at 2.1% of the global gross domestic product (GDP). For Bollen et al. (95) (*pink circles*), policy costs are derived from a set of four distinct scenarios and are calculated as GDP losses (cumulative discounted) relative to a no-policy baseline. Triangular schematics summarize the performance of scenarios from McCollum et al. (119) that achieve stringent fulfillment only for the objective(s) targeted under the corresponding policy frameworks (axis values normalized from 0 to 1 based on the full range of scenario ensemble outcomes). Sources: Riahi et al. (8), McCollum et al. (119), and Bollen et al. (95).

all of them simultaneously with integrated policies (rightmost bar/circle). For a discussion of the different welfare metrics used by the two studies, please refer to Section 4.3.

Both studies find substantial synergies across the different objectives. McCollum et al. (119) show that global policy cost reductions can materialize—particularly in the near term—if multiple objectives are pursued with integrated policies rather than in isolation. Note, for example, that the sum of the costs represented by the three leftmost bars is much greater than the costs represented by the rightmost bar. These cost synergies arise, for example, through reduced financial requirements for end-of-pipe air pollution control equipment and imported fossil fuels in a decarbonized energy system (see **Figure 3**). Similar findings have been made for regional assessments of the economic implications of cobenefits (57, 128, 129), but the literature reviewed here is the first to evaluate these effects on a global scale.

Other near-to-midterm synergistic effects of mitigation activities, also identified by Bollen et al. (95), include improved air quality (hence, lower health impacts) and enhanced energy security through fuel diversification by lowering the reliance on oil and gas demand and imports. As many of these synergies come about through energy and carbon intensity reductions, climate policy may be seen as a strategic entry point for reaping these benefits. It should be mentioned, however, that the cobenefits of stringent climate policies for energy security, air quality, and health, respectively, will be much less pronounced if future policies for air pollution and energy security are more aggressive than currently planned, as discussed in Section 3 (see 43, 69, and 120 for a detailed discussion of the implications of different air pollution control stringencies).

The integrated model studies presented in this section are the most comprehensive efforts to date in integrating many of the steps from the welfare-theoretical framework presented in Section 2 and showing conclusive quantitative results on a global scale. At the same time, these studies show the limits of integrating all these aspects into a single analysis framework. This is because they have to reduce the scope of analysis at each step, unlike in other literature strands, thus highlighting the value of each individual strand:

1. To keep model complexity manageable, these two studies focus on a smaller set of (energy policy) objectives, compared to the objectives considered in the sectoral research (literature strand 1, condensed in **Figure 2**) and even compared to model results on coeffects (literature strand 2, condensed in **Figure 3**).
2. Because these studies are each based on single models, the entire uncertainty range of deployment projections (see **Supplemental Material Section 1**) and the associated coeffects (as evidenced by the wide ranges from literature strand 2 in **Figure 3**) cannot be fully considered.
3. The determination of optimal levels of multiple objectives is prone to assumptions and value choices and largely hypothetical for nonmarket goods, so this small set of studies that analyze macroeconomic implications across multiple objectives reduce the complexity of the task by resorting to a range of simplifying assumptions. McCollum et al. (40), for instance, avoid explicit analysis of externalities and determination of welfare optima by considering a set of three possible stringency levels of policy targets from the political arena; this circumvents the (locally) contested nature of the priority levels attached to many objectives. By contrast, Bollen et al. (95) choose a relationship between income and the value of statistical life as well as specific parameters for the penalty function for energy security deficiencies and for the climate change damage function; these all predetermine the priority setting across the analyzed objectives; yet, despite the sensitivity analysis conducted, the choice of these values/parameters/functions does not cover the wide range of estimates available in the relevant literature.

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The analysis of additional objectives relevant for multiobjective decision making in the future would require consideration of the locally specific priority settings and policies, their nonclimate and climate effects on a global scale, and their implications for macroeconomic costs and welfare. Because such research is not yet available, Section 5 presents a complementary approach, which usefully juxtaposes sectoral research and integrated model results. Section 4.3 critically discusses the degree to which the integrated assessment of costs, benefits, and coeffects of mitigation can be embedded in a welfare framework, and how this depends on the modeling approach.

4.3. Critical Discussion of Policy Costs and Welfare Effects in Integrated Models

In Section 2, cobenefits and adverse side effects were introduced as part of a welfare-theoretic framework. We now show how the analysis of coeffects in integrated models can be related to this framework. Such models are dynamic numerical tools that explore the impact of transformational policies on the coupled energy-economy-environment system over a longer period of time (see **Supplemental Material Section 1**, for more details). By definition, such policies lead to nonmarginal changes in economic activity and social welfare. The related economic costs and welfare effects of a policy are usually measured against a counterfactual baseline case, which is used as a point of reference for the analysis. Integrated models come in various types (see **Supplemental Table 1** in the **Supplemental Material Section 3**) and thus have different capabilities of measuring the economic costs and welfare effects of policy changes. Two dimensions are relevant here: (*a*) the coverage of policy impact channels in terms of their economic costs and their benefits for societal objectives and (*b*) the degree to which (changes in) welfare can be measured.

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Concerning coverage of policy impact channels, most models provide estimates of the direct economic costs of climate policies measured, for example, in terms of reduction in household consumption or economic output (2; see discussion below). A small, but increasing, number of models are also capable of capturing the direct costs of additional policies aimed at other nonclimate objectives (see 40 and Section 4.2). Only a subset of models directly includes the economic benefits of policy intervention in terms of reduced climate damages (130–132; see 10 for a discussion). A full welfare analysis of costs, benefits, and coeffects of climate policy would require capturing the benefits and adverse effects of the whole policy portfolio on all relevant objectives and, in turn, the modeling of all impact channels through which the set of policies may alter the objectives (see 95 and Section 4.2). Such a complete CBA (e.g., following Equation 1) involves a series of heavily contested value judgments, is associated with a whole array of (additional) uncertainties in the valuation process, and hence remains a huge analytical and empirical challenge (cf. 10, 47). Those models that capture only policy costs are used for CEA, estimating the costs of reaching a set of predefined objective levels, for example, long-term climate targets (II in **Figure 1**) or targets for other objectives (III in **Figure 1**). Those models that additionally capture the policy benefits and residual impacts can also be used in a CBA mode to identify social welfare maximizing policies (IV in **Figure 1**).

Supplemental Figure 3, in **Supplemental Material Section 2**, shows how this welfare effect can be decomposed into policy cost and benefit components and how the range of cost and welfare estimates emerging in CEA and CBA applications, as well as climate damage estimates, relate to each other. For example, the policy costs in a multiobjective setting in the case of McCollum et al. (40) are estimated by a CEA, considering the policy benefits in physical terms only (e.g., health benefits), rather than in economic terms. By contrast, Bollen et al. (95) include the disutility of air pollution, climate change, and energy insecurity in their study. A thorough understanding of how cost and benefit estimates relate to a social welfare approach is essential for a meaningful comparison of costs and benefits to assess overall welfare changes. Nevertheless, information about the individual components of welfare changes shown in **Supplemental Figure 3** is also particularly useful to evaluate policy trade-offs. Such information can be deduced from an analysis of subsystems, includes a smaller set of uncertainties and assumptions, and is based on models with better system representation. For example, policy cost estimates based on CEA do not need to make assumptions about climate damages that are still highly uncertain, particularly on a global level (see 22 for a discussion).

A second source of difference between cost estimates of different integrated models is related to the degree to which welfare can be measured. Partial equilibrium models can only explore economic impacts on the sectors that are represented in the model. They usually express policy costs in terms of changes to consumer and producer surplus. Estimates of welfare changes require a general equilibrium framework that can capture the macroeconomic impacts of policies and changes to other objectives (see **Supplemental Table 1** in the **Supplemental Material Section 3**). Monetary measures of welfare change in general equilibrium frameworks include equivalent variation and compensating variation, which describe how income would need to change to keep households just as well off after the implementation of a policy as before. As these are quite difficult to calculate and communicate, proxy measures for welfare changes, such as changes in household consumption, are used more frequently in integrated models (1). Changes in GDP are also commonly used, although GDP is a less satisfactory measure of welfare changes because it only captures economic output, rather than the welfare benefit it generates (47).

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The introduction of a baseline scenario against which the welfare impact of a policy is measured gives rise to the notion of idealized (first-best) and nonidealized (second-best) policy environments (cf. 133). An idealized policy environment is one in which a single policy problem relating to a single objective exists; all other objectives are already achieved at their optimal levels in the baseline scenario (economically speaking, all externalities are already fully internalized). Economic theory stipulates that an idealized (first-best) policy consisting of ubiquitous Pigouvian pricing of environmentally damaging activities is optimal. In the case of mitigation, the idealized policy corresponds to comprehensive uniform GHG pricing in all sectors and regions, rising over time at a rate that reflects the cost increase of the next available unit of GHG emissions reduction. This is a useful analytical benchmark, included in most integrated modeling studies. However, coeffects do not have any value for society in such an idealized setting because the value of coeffects depends on the degree of internalization of existing externalities (34). These therefore need to be studied in nonidealized environments characterized by deviation from the optimal levels in more than one objective. In such circumstances, first-best policies may no longer be optimal (cf. 134). In some cases, climate policy could even lead to welfare losses if an already internalized externality was over corrected (34) or interacted with preexisting inefficiencies in a welfare-degrading way (135, 136; also cf. literature on the double dividend, e.g., 137, 138). For example, if a climate policy can adversely affect other objectives, overall mitigation costs can rise. If cobenefits are dominant, by contrast, mitigation costs can be lower or possibly negative, even before factoring in the direct benefits of reducing climate change (see **Figure 5**). How large the value of coeffects would be is an empirical question; a major research challenge for the next generation of climate policy assessments.

An even bigger challenge is to integrate the perspective across mitigation and adaptation. Integrated models were originally developed and are still used to prescribe optimal policy, including impacts and adaptation in addition to mitigation. However, the vast majority of scenarios reviewed by the IPCC was based on CEA rather than CBA and had a narrow focus on mitigation. This was mostly owing to the uncertainty in estimating impacts and adaptation, and their dependence on the geographical scale (see **Supplemental Material Section 1**). Mitigation, adaptation, and damages are, however, highly interconnected, and joint assessments are receiving renewed interest (139). Few integrated studies have quantified the competition between mitigation and adaptation in terms of the allocation of investments (140, 141). Others have looked into the implications of including adaptation strategies on equity in international climate policy (142, 143). In all cases, mitigation and adaptation strategies are found to be complementary but with potentially important repercussions on mitigation costs and strategies, especially in terms of regional differences.

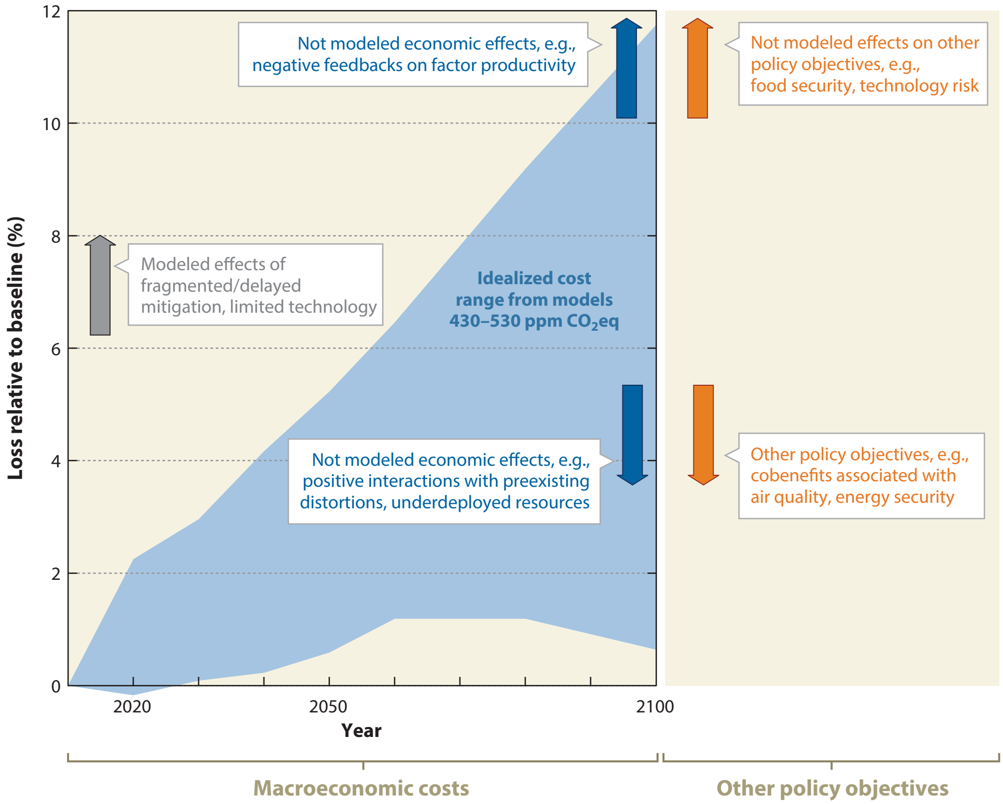

Figure 5

Stylized representation of mitigation cost impacts owing to considerations usually outside of those included in integrated models, such as coeffects. The plotted cost range refers to the percentage loss relative to baseline scenarios across models for cost-effective mitigation scenarios reaching CO_2-equivalent concentrations of 430–530 ppm (parts per million) in the year 2100 (25th–75th percentiles). Adapted from Krey et al. (133).

5. UNTAPPED POTENTIAL FOR FURTHER SYNTHESIS OF EXISTING RESEARCH

The review and condensation of literature on the coeffects of mitigation measures and pathways in Sections 3 and 4, respectively, show that interesting and important insights can be gained from the different strands of literature. Across these strands, there is, however, a trade-off between the number of objectives analyzed in a study and its ability to present aggregated quantitative results. This is mainly caused by the challenges of linking results from the integrated model literature on the one the hand to the sectoral literature on the other. Recent attempts to tackle this analytical separation from within the integrated model literature (Section 4.2) have improved the integrated understanding but are limited in scope because studies need to find the right balance in handling complexity, providing transparency, and dealing with computational limitations. This section suggests a complementary synthesis, juxtaposing (*a*) quantitative evidence from a wider set of mitigation scenarios from integrated models consistent with the 2°C target and (*b*) qualitative evidence on the potential coeffects of mitigation measures on a wider set of sustainability objectives from sectoral research. Although such a synthesis also faces limitations, it is able to draw on the respective strengths of the somewhat disparate literature strands: (*a*) the ability of the different integrated models to take into account cross regional and cross sectoral interactions of mitigation measures and (*b*) the ability of the sectoral studies, taken together, to take into account the coeffects on a wider set of sustainability objectives and at a more disaggregate, detailed level.

Energy intensity (EI): the ratio of energy use to economic or physical output

In this context, **Figure 6** presents the different sets of results in such a way that they speak to each other and so increase the understanding of relevant coeffects owing to global mitigation pathway choices. The table draws on data for energy supply and demand projections (in primary and final energy terms, respectively) that are presented by a large group of integrated models for different sets of scenarios (from the WGIII AR5 Scenario Database, **https://secure.iiasa.ac.at/web-apps/ene/AR5DB**). Ranges of scenario results are shown for those indicators that can be linked directly to the (groups of) mitigation measures for which coeffects are presented. Integrated models usually include all relevant energy supply technologies; however, the number of sectoral mitigation measures far exceeds the current limitations of complexity of the models. For each demand sector, the table therefore focuses on the range of projections for total sectoral energy demand. It also centers on those high-carbon energy carriers that are most widely used today and whose reduction is linked most directly to the cobenefits presented on the right side. Finally, it shows the median projections of sectoral demand for electricity and bioenergy, which are the most important low-carbon energy carriers (see **Supplemental Material Section 4**). To show the effect of climate policies on the energy supply and demand projections, the table shows baseline versus mitigation scenarios consistent with the 2°C target (as an illustration). This is for both standard (black ranges) and for low energy-intensity (EI) assumptions (blue ranges) in which the rate of EI reduction is consistent with and greater than historical developments, respectively. The table thus allows the coeffects of the sectoral mitigation measures to be linked to the projected changes in crucial energy indicators. Even though the ranges are often wide, the changes in the median projections consistently show the following:

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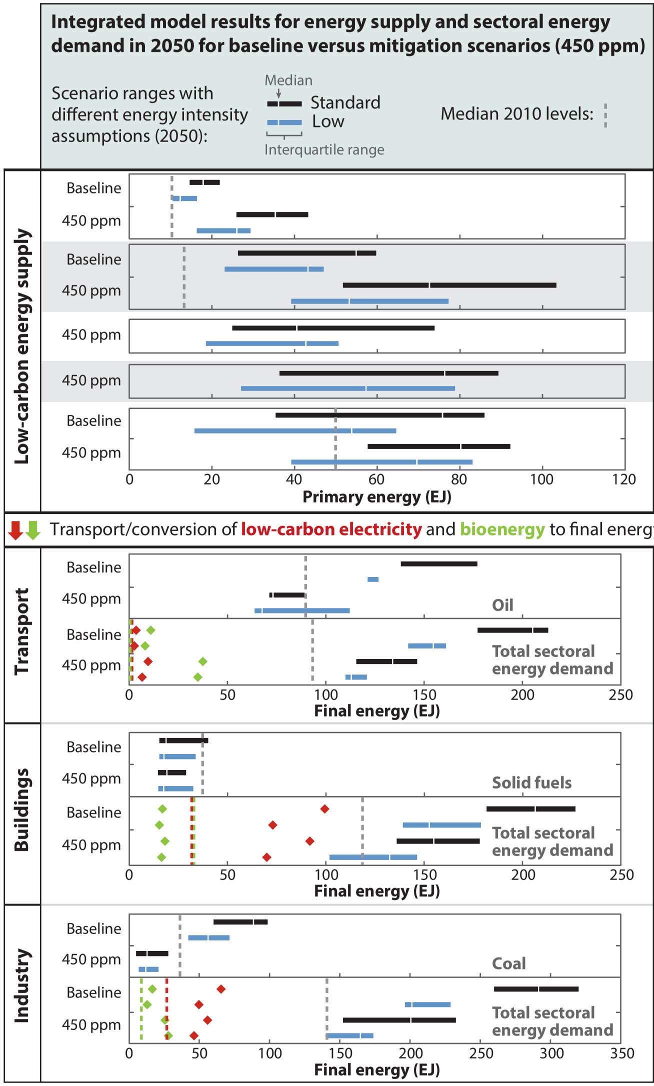
1. Increased attempts to achieve EI reductions in baseline scenarios (i.e., without targeted climate policies) lead to reduced demands and supplies of energy carriers in all sectors against the baseline; this implies that there would be a substantial number of potential cobenefits, particularly owing to reduced impacts of those energy carriers that are associated with the largest adverse side effects (oil, traditional biomass, and coal; see **Supplemental Material Section 4**). However, relying solely on optimistic EI reductions, without having a dedicated climate policy, does not allow the 2°C target to be achieved (1) as it only slows the growing oil and coal demand and may generate rebound problems (see Section 2).
2. Projections for mitigation scenarios with standard EI assumptions not only require demand reductions against baseline and today's levels of oil and coal use but also result in an increased demand for biofuels and electricity from low-carbon sources. The balance of the local coeffects primarily depends on how and where the additional bioenergy is produced and which low-carbon electricity supply technologies are deployed where to satisfy the additional electricity demand (Section 3 and **Supplemental Material Section 4**).

Figure 6

Scenario results from integrated models consistent with a 2°C target for different energy supply and demand indicators and the potential coeffects of (groups of) sectoral mitigation measures on additional sustainability objectives. Only scenarios with immediate mitigation and full availability of technologies are shown. Mitigation scenarios with CO_2-equivalent concentrations of 430–480 ppm (parts per million) in the year 2100 are indicated by 450 ppm. For details, see section 6.1.2 and table 6.2 in Clarke et al. (1). Dark green arrows/text, potential cobenefits; orange arrows/text, potential adverse side effects; smaller arrows, smaller effects by comparison (see **Figure 2** for details and notes). Abbreviations: BECCS, bioenergy and CCS; CCS, carbon dioxide capture and storage; CO_2, carbon dioxide; EJ, exajoule.



Sector	Sectoral mitigation measures in energy supply and energy demand sectors	Economic: Energy security	Economic: Sectoral productivity	Economic: Local/sectoral employment	Social: Reduced health impact	Social: Thermal comfort, work conditions	Social: Safety/disaster resilience	Environmental: Reduced eco-system impact	Environmental: Reduced water use/pollution	Environmental: Reduced land use	Other objectives
Low-carbon energy supply	Nuclear (Replacing coal)	↑		↑	↑↓		↓	↑↓			Nuclear proliferation, nuclear waste
	Renewable (excluding bioenergy) (Replacing coal)	↑		↑	↑			↑↓	↑↓		Energy access, particularly off-grid; Increased resource mining
	Coal with CCS (Replacing coal)			↑↓	↓		↓	↓	↓		Long-term monitoring of CO_2
	BECCS (Replacing coal)				↓		↓	↓	↓		
	Bioenergy (without CCS)	↑		↑↓	↑↓			↓	↓	↓	Food security and equity in land tenure
Transport	Fuel switching	↑			↑		↓	↑↓			Technological spillovers
	Technical energy efficiency	↑			↑		↑	↑			
	Urban form/modal shift	↑	↑	↑↓	↑		↑	↑		↑	Equitable mobility access
	Energy demand reduction via other means	↑	↑		↑			↑↓		↑	Reduced urban congestion
Buildings	Fuel switching	↑		↑	↑			↑			Reduced fuel poverty
	Technical energy efficiency	↑	↑	↑	↑↓	↑	↑	↑	↑		
	Energy demand reduction via other means	↑			↑			↑			
Industry	Fuel switching		↑		↑	↑		↑	↑		Increased competitiveness
	Technical energy efficiency	↑	↑	↑	↑	↑	↑	↑	↑		Technological spillovers
	Material efficiency			↑	↑		↑	↑			Reduced resource mining

3. Increased attempts to achieve EI reductions in mitigation scenarios lead to the lowest demand for all fossil-based energy carriers as shown in **Figure 6**. The additional supply of low-carbon electricity and bioenergy is lower than that of mitigation scenarios with standard EI assumptions. Maximizing synergies and minimizing trade-offs with nonclimate sustainability objectives hence require that climate (and nonclimate) policies be chosen in such a way that certain adverse side effects of bioenergy production are either avoided or carefully managed (24–26, 29, 102, 109, 113, and bioenergy supply in the **Supplemental Material Section 4**) and that low-carbon, but risky, energy supply technologies (e.g., nuclear and carbon dioxide capture and storage) are deployed in situations where they generate the lowest adverse side effects (see 21, 118, and energy supply in the **Supplemental Material Section 4**).

Carbon dioxide capture and storage (CCS): CO_2 from industrial and energy-related sources, which is captured, conditioned, compressed, and transported to a long-term storage location

Supplemental Material

This synthesis offers a useful opportunity to draw on different strings of evidence from the somewhat disparate strands of literature at one glance and potentially increases our understanding of the implications of mitigation policy choices. Yet, **Figure 6** offers neither quantitative results on the net global coeffects nor their impact on overall social welfare. To mitigate this shortcoming and better adapt these findings to the specific circumstances, this exercise could be repeated for those disaggregated scales that are still supported by the integrated models (for up to about two dozen world regions). This would give decision makers the opportunity to interpret the results against the background of regional contexts and priority settings (see, e.g., 39), circumventing some of the challenges of welfare accounting discussed in Section 4.3.

6. CONCLUSION AND OUTLOOK

Based on a welfare-theoretic framework, the review and condensation of the WGIII AR5 results in this article show that the different strands of literature on coeffects have focused on different aspects of the interactions of climate change mitigation and other sustainability objectives; each strand of literature considered independently has remained partial in its ability to generate insights. This article also reveals that quantification and aggregation of coeffects are challenging because of the incommensurability and uncertainties of results that are all the more pervasive (*a*) the more the perspective shifts from sectoral and local to economy wide and global, (*b*) the more objectives are taken into account in the analysis, and (*c*) the more the results are expressed in economic rather than nonmonetary terms.

Despite the growing insights into the coeffects of mitigation measures and recent efforts to conduct more integrated research, there are still substantial trade-offs (*a*) between the number of objectives analyzed and the ability to present quantitative results, particularly for overall welfare implications; and (*b*) between capturing synergies and trade-offs across different levels to inform global coordination and providing context-specific information necessary for local/sectoral policy making.

Literature strand 1 is able to analyze the effect on many objectives at a high degree of sectoral detail, and its meta-analysis in **Figure 2** points to the important role of energy-efficiency improvements and other measures to reduce energy demand. The associated results are, however, very challenging to aggregate, particularly in monetary terms and on a global level. One reason for this is that they do not take into account cross sectoral or cross regional interactions—a prerequisite for cost-effective mitigation. Although literature strand 2 develops a better understanding of cost-effective mitigation pathways with respect to their implications for global coeffects in quantitative terms, revealing the salience of energy security and air quality cobenefits, it only analyzes a limited number of objectives. Lastly, literature strand 3 offers important insights into the welfare implications of pursuing three energy policy objectives either simultaneously or in isolation and reveals that climate policy is a good entry point to realize synergies across these objectives. The number of objectives analyzed is even smaller than in the second strand as is the ability to reflect the full range of uncertainty across different models. Future work can build upon these efforts.

To relax this trade-off to some extent, we present a way forward that draws on the existing strings of scientific evidence and builds on the respective strengths of the different literature strands without integrating them into a common modeling framework. Section 5 brings together in one table (*a*) quantitative evidence on the future energy supply and demand in different sectors from a wider set of mitigation scenarios consistent with the 2°C target and (*b*) qualitative evidence on coeffects of mitigation measures on a wider set of sustainability objectives from sectoral studies. Although this approach does not eradicate the pervasive incommensurability and uncertainties, it makes them more transparent and accessible to decision makers. This synthesis tool allows decision makers to gain a better overview of, and to extract high-level insights into, the complex interactions of multiple objectives, revealing the following:

1. Mitigation pathways consistent with the 2°C target lead to a whole range of potential cobenefits and lower risks by reducing the use of fossil fuels and traditional biomass against baseline developments (and often current use); higher demand for low-carbon energy carriers might increase supply-side risks in specific local circumstances.
2. Faster-than-historical EI reductions lead to potential cobenefits and reduced risks in all sectors, irrespective of the scale of targeted global mitigation efforts. Combining optimistic EI reductions with stringent mitigation efforts leads to higher cobenefits and lower risks compared to mitigation pathways with standard EI reductions by reducing the demand for fossil fuels and traditional biomass and increasing the flexibility of choice between alternative mitigation measures. This allows better management of mitigation risks on the supply side associated with the upscaling of low-carbon energy technologies and bioenergy supply.

The good news is that most risks on the supply side, which increase with the stringency of the mitigation goals, occur at the local scale and can be managed locally or nationally (except, perhaps, nuclear proliferation risks and the global aspects of food insecurity). Decision makers at the local/national level can exploit the increasing level of knowledge and the flexibility implied by the large range of results from mitigation scenarios (see **Supplemental Material Section 1**) to choose climate policies and mitigation measures according to their priorities for sustainability objectives. On the basis of existing literature, however, it is not possible to analyze the coeffects of these (sub)national measures on multiple objectives and their global mitigation effects in an integrated way, and vice versa, at least not for more than a small number of energy objectives (see Section 4.2). Despite a better understanding of the potential coeffects of different sets of mitigation pathways for a broader set of objectives (presented in Section 5), scientific evidence thus far only offers limited guidance for decision makers who seek to understand under which conditions and at which level synergies across multiple objectives can actually be realized and trade-offs avoided. Future research could advance the understanding of these complex interactions in three possible ways.

Supplemental Material

First, given that the trend is toward increased subnational- and national-level climate legislation and policy and that international cooperation is also increasingly focused on leveraging and enhancing these national measures (19, 144), greater attention to consolidating and summarizing coeffects at the national scale would be particularly helpful (see, e.g., 145). Similarly, there has been a proliferation of subnational decision making on climate issues, and other sustainability objectives (e.g., urban air quality) are almost exclusively handled at this level (18, 19). To serve these needs, future research should develop a multidimensional typology of coeffects beyond the classification into sectors, local or global effects, and sustainability aspects presented in **Figure 2**. This could then be used to target the specific types of challenges associated with the realization of synergies and the avoidance of trade-offs to more specifically target coeffects that map to decision-making jurisdictions, such as cities, states/provinces, and countries. For example, the typology could differentiate more explicitly among the coeffects that accrue locally and are primarily driven by local decisions (e.g., mobility access), those that accrue locally but are primarily driven by decisions made within the broader region (e.g., local agricultural yield gains through methane mitigation elsewhere), and those that accrue globally but are primarily driven by decisions made locally (e.g., technological spillovers). Other dimensions could include distributional, geographical, or timing aspects (i.e., which societal groups or stakeholders are most affected, and where and when they are affected). This would be useful for research that could choose the most appropriate methods, models, and system boundaries as well as for the political process that could focus on the most salient aspects of the interactions of multiple objectives.

Second, such a typology could be useful for a broader modeling strategy that could draw on the strengths of different methods by combining global-scale integrated models (which take into account cross sectoral and cross regional interactions) with national and subnational models (which are more spatially disaggregated and may have greater technological and sociodemographic details and heterogeneity). Although it may be too much to expect the hard coupling of these different tools, careful analyses within the framework of internally consistent scenario studies could permit a better accounting of national/local circumstances and preferences (along with their aggregate global/regional consequences), such as the level of socioeconomic and technological development, distributional aspects, risk perceptions, and priority settings for nonclimate objectives.

Third, from a risk-management perspective, it is particularly important to differentiate between risks that can be managed locally (e.g., landscape impacts) and risks that can build up globally (e.g., for food security and nuclear proliferation). Future research could draw on the recent advances of integrated modeling with respect to more elaborate real-world assumptions for mitigation pathways, taking into account delayed and fragmented global mitigation efforts as well as the limited availability of mitigation technologies. Understanding the synergies and risk trade-offs across multiple sustainability objectives for alternative mitigation pathways would be an important contribution to a better-informed decision-making process at global and national/local levels.

Because many authors have argued for a more integrated policy approach to advance mitigation and additional sustainability objectives (e.g., 7, 10, 28, 39, 41, 43, 44), partly dissolving the analytical separation between the different sets of scientific evidence as done in this article is highly relevant for climate and sustainability policy choices. Better knowledge about the potential synergies and trade-offs across multiple objectives improves the understanding of this ends-means interdependency and may, according to Edenhofer & Kowarsch (31), even encourage decision makers to adapt existing priority settings to release political gridlocks, e.g., in international climate policy (cf. 146).

SUMMARY POINTS

1. The literature documents a large potential for cobenefits of mitigation for nonclimate objectives, such as human health and energy security, but little is known about aggregated results and their overall welfare effects, particularly on a global scale.
2. Integrated model studies highlight that climate policies as part of well-designed policy packages reduce the overall cost of achieving multiple sustainability objectives but do not offer a systematic analysis of mitigation risks.
3. The incommensurability and uncertainties around quantification of coeffects become increasingly pervasive the more the perspective shifts from sectoral and local to economy

wide and global, the more objectives are analyzed, and the more the results are expressed in economic rather than nonmonetary terms. This reveals a trade-off between the number of objectives analyzed in a study and its ability to present aggregated quantitative results.

4. Drawing on different strings of evidence highlights the role of energy-efficiency and other measures to reduce energy demand for realizing synergies across multiple sustainability objectives and hedging mitigation risks on the supply side.

FUTURE ISSUES

1. Future research should develop a multidimensional typology of coeffects beyond the classification into sectors and sustainability aspects to inform (*a*) the choice of methods, models, and system boundaries in the analysis of a particular effect; and (*b*) the political process that could then focus on the most salient interactions of multiple objectives.
2. Greater attention to consolidating and summarizing coeffects at the local/national scale would be particularly helpful to better map to decision-making jurisdictions and the respective circumstances, preferences, and priority settings.
3. Future modeling efforts should draw on the strengths of different methods by combining global-scale integrated models (which take into account cross sectoral and cross regional interactions) with national and subnational models (which are more spatially disaggregated and may have greater technological and sociodemographic detail and heterogeneity).
4. Understanding the synergies and risk trade-offs across multiple sustainability objectives for alternative mitigation pathways would be an important contribution to better-informed decision-making processes at global and national/local levels, drawing on the recent advances of integrated modeling with respect to more elaborate real-world assumptions, such as delayed and fragmented global mitigation efforts as well as limited availability of mitigation technologies.

DISCLOSURE STATEMENT

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