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Perspective

Improving Climate Change Mitigation Analysis: A Framework for Examining Feasibility

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SUMMARY

Limiting global warming to 2°C or less compared with pre-industrial temperatures will require unprecedented rates of decarbonization globally. The scale and scope of transformational change required across sectors and actors in society raises critical questions of feasibility. Much of the literature on mitigation pathways addresses technological and economic aspects of feasibility, but overlooks the behavioral, cultural, and social factors that affect theoretical and practical mitigation pathways. We present a tripartite framework that "unpacks" the concept of mitigation pathways by distinguishing three factors that together determine actual mitigation: technical potential, initiative feasibility, and behavioral plasticity. The framework aims to integrate and streamline heterogeneous disciplinary research traditions toward a more comprehensive and transparent approach that will facilitate learning across disciplines and enable mitigation pathways to more fully reflect available knowledge. We offer three suggestions for integrating the tripartite framework into current research on climate change mitigation.

INTRODUCTION

The 2018 IPCC Special Report emphasized the risks associated with global warming of 1.5°C and higher above pre-industrial levels and concluded that current technological solutions alone are insufficient to limit warming to 2°C, much less 1.5°C.[1] To reach these objectives within a few decades, all actors in society, including governments, private organizations, and citizens, will need to change.[2] These changes concern both activities directly influencing greenhouse gas emissions (GHG) and ones affecting context, such as the governance processes of the energy system, and other activities, such as agriculture and forestry.[3]

Achieving climate change mitigation objectives entails unprecedented common-pool resource management at a global scale that will integrate actions across scales and actors.[4–6] A key question is how much of this is feasible. Most of the literature on mitigation pathways concentrates on the technological and economic aspects of feasibility. The interactions of actors that determine which actions can be taken and their success are at best implicitly considered. In this Perspective, we present a tripartite framework for assessing feasibility that offers a platform for coordinating this immensely complex action agenda and management task. We argue that the framework, which considers technical potential (TP), initiative feasibility (IF), and behavioral plasticity (BP), can facilitate the integration and streamlining of research programs across scientific disciplines, permitting a fuller depiction of the opportunities for climate change mitigation and their practical feasibility. If these three

Table 1. Glossary of Key Terms

Term	Definition
Adoption	A choice to undertake an initiative, to shift to a different technology, or to alter a behavior
Actual mitigation	Degree of mitigation, typically expressed as CO_2 equivalents, resulting from an initiative
Behavioral plasticity	The extent to which the target of a mitigation initiative, as implemented, responds to it as intended. Behavioral plasticity is a function of attributes of the targets, their contexts, and the ways mitigation initiatives are implemented
Change agent	An individual, social movement, or public or private organization that undertakes initiatives to mitigate harmful environmental changes
Implementation	The degree to which an initiative, once adopted, is supported by providing adequate resources and monitoring and designed for optimal influence on the target actors
Initiative feasibility	The likelihood that a change agent will adopt and then implement a mitigation initiative
Maintenance	The degree to which a target actor continues a behavioral change over time or keeps an adopted technology functional
Mitigation initiative	An action by a change agent, such as an individual, government, corporation, non-governmental organization, or social movement, that could realize mitigation opportunities. These might include public laws, policies, or programs, or corporate supply policies, community agreements, and other activities of a change agent to influence a governmental or private actor to mitigate climate change
Mitigation opportunity	A pathway toward achieving mitigation of climate change. Opportunities can be seen in emerging technologies that enable mitigation (e.g., electric vehicles, meat substitutes, carbon capture and storage) or in domains or types of human activities where mitigation can happen (e.g., travel, meat consumption, energy use in manufacturing, reforestation). The extent to which an opportunity results in actual mitigation depends on the initiatives undertaken to realize the opportunity and on responses to the initiatives
Target actor	An individual, community, organization, or government entity that might respond to a mitigation initiative
Technical potential	The reduction in the drivers of climate change—typically expressed as emissions reductions in CO_2 equivalents—that would result if a mitigation opportunity were completely realized or an initiative fully achieved its objectives

factors are addressed explicitly, this framework can also help accelerate transdisciplinary communication and the accumulation of knowledge. Despite focusing here on climate change mitigation at the global level, we note that the framework's application could extend to national and local mitigation efforts as well as to environmental change and sustainability transformations more broadly.

MITIGATION OPPORTUNITIES, INITIATIVES, AND FEASIBILITY

A number of climate change mitigation objectives and pathways toward them (from now on referred to as "mitigation opportunities") are frequently identified in discussions of national and global climate policy. These include introducing new technologies for energy efficiency, low and zero-carbon energy and negative CO_2 emissions; reducing non-CO_2 emissions; stopping or reversing deforestation; changing lifestyles; and halting population growth. We use the term "mitigation initiative" to refer to actions by change agents, such as individuals, governments, corporations, non-governmental organizations, and social movements, that could take advantage of mitigation opportunities. Initiatives might include command and control regulations, financial incentives (e.g., taxes, pricing), programs to encourage specific behaviors, investment and procurement requirements and practices, and other efforts to promote mitigation technology adoption and other mitigation actions, all of which interact. New initiatives will be needed to achieve both supply- and demand-oriented mitigation opportunities[7,8] and to change the behavior of various target actors (from now on referred to as "targets of change"), including households and organizations in the public and non-governmental sectors.[9–14] See Table 1 for definitions of key terms.

As the distinction between opportunities and initiatives indicates, opportunities for mitigation are not automatically seized and do not necessarily achieve their potential. Their implementation is limited by what the IPCC refers to as "economic, financial, human capacity, and institutional constraints," including limited acceptance of new policies, technologies, and practices.[1] Given these constraints, the IPCC special report[1] defines feasibility as "the capacity of a system as a whole to achieve a specific outcome," but subsequently only addresses the feasibility of mitigation opportunities at the global level. Although global feasibility assessments are useful, they underplay the fact that

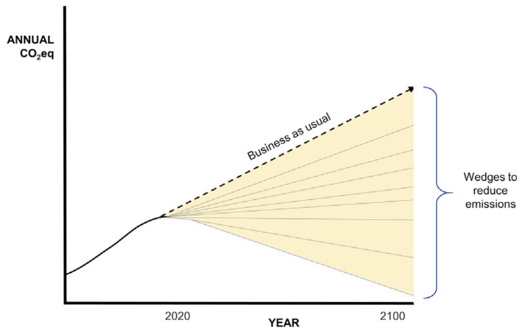

Figure 1. Conceptual Diagram Representing CO2-eq. Wedges to 2100

Each wedge represents the impact on CO2-eq. emissions over time of a mitigation opportunity, after implementation. We present the trajectories as linear but in reality, they would have more complex dynamics.

feasibility is highly dependent on context, as it varies across and within countries; across technologies and initiatives; across the individuals, organizations, or social systems that are both agents and targets of initiatives; and over time.[9,15–17] The concept of feasibility combines two elements: the potential for change agents to adopt and implement initiatives (IF)[10,18,19] and the extent to which the targets of initiatives respond to them as intended (BP).[15] We elaborate on these distinctions below. Initiatives can be analyzed for their potential to provide "wedges" as illustrated in Figure 1, a diagram showing the transition over time from current trajectories of climate forcing to a desired objective.[15,20]

Figure 1 indicates how various mitigation opportunities could contribute to reducing the human climate footprint over time given their TP, IF, and BP. We use the term wedge because our approach is inspired by the work of Pacala and Socolow,[20] but we go beyond the original formulation, which mostly focused on TP, and we take further inspiration from recent special reports that encourage us to consider IF and BP.[21,22] Figure 1 follows Pacala and Socolow's diagram by showing linear change,[20] but we expect non-linear growth over time in the impacts of mitigation initiatives. We are calling for the kinds of analyses needed to quantify the figure, and until that analysis is in place the trajectories displayed must be stylized and hypothetical.

As an example, consider the potential impact of a behavioral change, such as reducing the meat-intensity of diets. The TP is large as illustrated by a number of analyses.[23–25] However, the feasibility of achieving this opportunity will, to a large extent, depend on public acceptance of initiatives to produce the change, on the efforts of other actors to block such initiatives (e.g., lobbying and advertising by meat producers), on the development of successful meat substitutes, and on cultural and social norms around meat consumption. All of this is not only influenced by climate considerations but also other concerns (e.g., food security, health, taste preferences).[26] The meat example indicates the many factors that need to be assessed to understand "feasibility" and to capture and act upon opportunities for widespread mitigation.[27–29] Assessing the barriers to fully realizing mitigation opportunities requires much greater integration of concepts and analyses from the non-economic social and behavioral sciences than has been deployed in the past.

The IPCC reports have started to pay attention to broader feasibility considerations, but much more can be done.[30] To inform humanity's efforts to achieve climate stabilization objectives and goals for equitable and sustainable development, assessments by IPCC and others should include an explicit, transparent assessment of IF and BP. The assessment should examine international, regional, national, and non-state initiatives. It should also involve a wider range of disciplines, including sciences looking at behavioral, organizational, political, and cultural aspects and at polycentric governance involving actions by governments and private actors.

LIMITS OF EXISTING ASSESSMENT FRAMEWORKS

Model-based scenarios and technology studies are key inputs into the IPCC assessments. A strong focus on economic and technological aspects of GHG emissions reduction characterizes the scenario literature that underpins IPCC assessments.[31] This includes scenarios created by individual modeling teams, community scenarios, such as the Representative Concentration Pathways,[32] and mitigation scenarios derived from the Shared Socioeconomic Pathways (SSPs).[33]

The main models used to create the scenarios assessed by IPCC are integrated assessment models (IAMs), energy system models, and computable general equilibrium models. Such models are generally used not to predict future emissions trajectories but to generate self-consistent accounts of ways in which a prescribed emissions trajectory might be achieved. In many model applications, initiatives are represented by a financial cost imposed on emissions or technologies, resulting in changes to the prices of different energy sources that in turn determine actual mitigation. The motivation is not to represent only financial policy instruments, but also to identify low-cost mitigation opportunities. Examples exist of applications in which other types of policies are implemented.[34–36] The insights from engineering, economics, and physical sciences can often be translated into the modeling world via equations. This quantification is less well developed for insights about social and behavioral factors affecting feasibility, such as policy implementation, lobbying and social movement activities, organizational dynamics, or psychological processes that entrain values, beliefs, and norms.[37,38] These are often represented implicitly, for instance, in scenario storylines, but that approach makes it hard to link back to the research literature. Some efforts are underway to incorporate explicit psychological models of consumer behavior into modeling.[39,40] As the IPCC moves forward to incorporate a richer treatment of initiative-related processes, including those of both governments and non-governmental actors and a broader set of actors that can be change agents and targets of initiatives, it will be helpful to have a framework for explicitly assessing and analyzing social, cultural, behavioral, organizational, and political aspects of policy and decision making.

The most common approach to developing mitigation scenario analysis, i.e., using the explicit or implicit price of GHG emissions, leads to bias in the type of strategies that are assessed. For example, the economic consequences of switching from fossil fuels to low and zero GHG-emitting technologies can readily be evaluated within such a framework, as can the consequences of long-term reductions via so-called carbon dioxide removal options (reforestation, bioenergy with carbon capture and storage) versus rapid short-term reductions in fossil fuel use. However, it is relatively hard to represent explicitly in models the interests of different societal groups and the interactions between these groups in pushing their favorite response strategies. This also means that often more attention is paid to cost-optimization than to non-price considerations (e.g., norms, values, and equity concerns).[9,19]

Recently, there has been an increasing focus in the model-based scenario literature on the evaluation of technologies to increase energy efficiency.[41,42] But again recent modeling work is limited by difficulties in representing behavioral responses and institutional factors that affect adoption. As a result, studies that do focus on behavioral change either make stylized assumptions (full adoption of sustainable behavior in a certain year),[42] or formulate storylines outside models. However, it is possible to make better use of the social science literature. For example, agent-based models could offer an effective strategy for incorporating broader social science understandings into models, but they are, as yet, less well honed than IAMs for addressing current policy questions.[43]

Other work on energy demand has included efforts to capture the impacts of increasing average incomes, levels of urbanity, education, and other factors on emissions.[44–47] But even these efforts could benefit from building on the substantial literature on anthropogenic drivers of environmental stress in general and GHG emissions in particular.[48,49] Efforts to connect such analyses to potential initiatives either focus narrowly on one or a few drivers (for instance, failing to address potential positive and negative behavioral spillovers),[50–54] and/or make simplistic assumptions about initiative effectiveness.[55]

One key question about the pathways from mitigation opportunities to actual mitigation is whether particular initiatives to promote these opportunities are feasible: Can they be adopted and implemented? The concepts of technical and economic feasibility are relatively well defined and readily address such questions as these: Which technologies could be scaled to achieve certain mitigation objectives? Which initiatives could be implemented at a cost that makes them attractive economically? Such analyses are necessary in considering which strategies merit further attention. But they do not consider social feasibility. For example, public policies typically need to have sufficient societal support to be adopted. Experiments to implement carbon capture and storage have been canceled in several countries, not for technological or economic reasons but due to societal opposition. The expansion of wind power programs and the adoption of carbon taxes are also controversial in some jurisdictions despite usually offering economic benefits as indicated by technical analyses.[56,57] In many areas of the world, cost-effective utilization of renewable energy will require new transmission corridors that, although economically feasible, often face substantial local opposition.[58] For example, in some jurisdictions in the United States, partisan polarization is undermining the ability of democratic processes to adopt climate mitigation initiatives even when the majority of citizens support such action.[59]

Full implementation of initiatives also cannot be assumed. Carbon taxes, for example, can sometimes be evaded by shifting emissions to untaxed jurisdictions, and so carbon pricing policies within a nation would have to consider the climate footprint of imports and develop appropriate policy responses.[60–62] Government agencies might lack resources to monitor compliance with regulations. Current assessments and modeling studies still struggle to take these aspects of feasibility into account.

A TRIPARTITE FRAMEWORK

We present a tripartite framework for unpacking the concept of feasibility that offers a structured and transdisciplinary approach to better incorporate issues of feasibility and context specificity into assessments of mitigation opportunities. Our emphasis is on informing ongoing scientific and analytical efforts to improve mitigation scenarios, including those deployed in the ongoing IPCC assessments. The framework could also inform future research on environmental change and sustainability transformations more broadly by providing a way to better integrate social science.[63,64]

The tripartite framework considers and integrates three factors: TP, IF, and BP (see Figure 2).[10,15] It also considers the time scales of change.[9] TP refers to the reductions in the drivers of climate change—typically expressed as emissions reductions in CO_2 equivalents—that would result if a mitigation opportunity were completely realized or an initiative fully achieved its objectives. For example, the TP of electric vehicles is the CO_2-eq. reduction achieved if all conventional vehicles were replaced.[65,66] However, actual mitigation also depends on the extent to which potential initiatives to encourage electric vehicles can be implemented (IF),[10] and on the extent to which, once implemented, the initiatives result in the intended behavior change (BP).[15,67] Thus, for any mitigation opportunity, there are many ways to try to achieve its TP, and these can vary greatly in terms of IF and BP. Continuing with the example of electric vehicles, IF is a factor for both governmental and private initiatives. IF involves the likelihood that governments will enact and implement incentives for production or purchase of the vehicles. It also involves initiatives by manufacturers to initiate production and to promote the sale of the vehicles and by large organizations to buy electric vehicles for their fleets and provide charging stations for their employees and customers. Thus, feasibility analysis should consider all such factors.

BP includes the proportion of manufacturers and fleet owners that respond to pressure from governments and social movements to manufacture, market, and purchase the vehicles. It also includes the proportion of individual vehicle owners who actually switch to electric and the extent to which their electric vehicle trips replace conventional vehicle trips.

Diet change can also be represented in terms of TP (mitigation that would be achieved by diet change across a population), IF (e.g., initiatives to provide and promote affordable vegetable-based food products that fit consumers' preferences), and BP (the actual adoption of new food products). When IF and BP are considered, actual mitigation falls far short of TP.[15]

The arrows in Figure 2 indicate causal links or influences. The effect of an opportunity or initiative on actual mitigation is its TP modified by IF and BP. In the case where IF and BP can be represented as percentages, actual mitigation is the product of TP, IF, and BP. The reciprocal arrows between IF and BP indicate that the ways initiatives are implemented can alter BP (e.g., by reducing barriers to behavioral change)[68] and that the targets

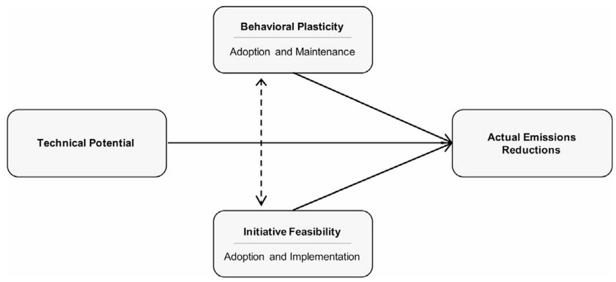

Figure 2. The Tripartite Framework: Pathways from Mitigation Opportunities to Their Climate Impact

of change can make initiatives easier or more difficult to adopt and implement (e.g., by support for or opposition to public policies or requests to employers to install charging stations). In addition, understandings developed in analyzing and experimenting with initiatives can lead to new ideas about technology, so feedback can occur from BP and IF back to TP in the long run, but for simplicity we leave those paths out of the diagram.

Change agents might intervene through various instruments. A common typology of public policy instruments distinguishes regulatory, financial, and ''behavioral'' initiatives (e.g., appeals to social or personal values and norms, and altering choice architecture).[69–73] These instruments are often aimed at specific actions by specific target actors, although some financial incentive policies, such as carbon taxes and carbon trading regimes, have broader targets. Other instruments for reducing climate footprints include technological research and development, changing physical infrastructure, pressure from social movement organizations, and investors' choices that express climate concern. Whatever instruments are used, their ultimate impacts depend on IF, BP, and time frames.

IF is specific to change agents, which might be governmental or non-governmental. It includes two elements: initiative adoption and implementation. With public policies, adoption depends on political feasibility, which often includes factors, such as public support for the policies, pressure from interested and affected parties and their organizations, and political negotiations in legislative bodies.[74–77] With private initiatives, adoption depends on pressures from outside the organization and sometimes on pressures from within.[78–80]

Implementation of an initiative is affected by numerous factors, including the financial and organizational capabilities of the implementing actor to monitor and enforce compliance. For example, if a carbon tax is adopted, its effectiveness can be reduced by poor implementation, such as inadequate emissions monitoring. Many public and private initiatives will require the elaboration of definitions, practices, and measurements, often called ''standards,'' that affect the mitigation achieved by the initiative and are another venue where various groups can exert their influence.[69] Non-governmental initiatives also face difficulties of implementation.[81,82] Understanding of IF comes mainly from research on political and organizational decision making and from assessments of specific potential initiatives in particular contexts.

BP is specific to the targets of change initiatives, which might be consumers, other actors in the supply chains of goods and services, investors, or others. It is the extent to which these targets respond as intended by the change agents who adopt and implement an initiative. We emphasize that BP is dependent on the ways that initiatives are designed and implemented within what is feasible (e.g., marketing efforts, engagement of target communities, efforts to simplify choices).[11,68,83,84] BP includes two elements: the targets' adoption of new, lower-emitting technologies and behaviors, and the degree to which these actions are maintained. Adoption of a technology or behavior by target individuals and organizations depends on the availability of financial resources to adopt costly innovations, the ability to undertake the cognitive effort needed to make well-informed choices, and, within organizations, the division of responsibilities across subunits.[9,85] Use and maintenance of a target technology or behavioral pattern depends on such matters as individual, group, and organizational norms; ingrained habits and routines and the establishment of new ones; and beliefs about the benefits and costs, broadly defined, of maintaining the new technologies or behavioral patterns.[11,68,86–88] Adoption, maintenance, and use of technologies are specific to the technology and to the target actors' contexts. Understanding of BP comes mainly from the sciences of individual, household, and organizational decision making and cultural change, including branches of anthropology, behavioral economics, decision science, organizational studies, psychology, and sociology.

For any initiative, IF and BP interact in complex ways, and positive and negative externalities might exist between different initiatives. These externalities include effects from behavioral spillover,[53] where one initiative can make another initiative targeting the same target actors more or less feasible and effective, or from telecoupling,[89] where an initiative implemented in one location has consequences for the BP and IF of initiatives in other locations. A recent study supports the possibility of negative spillover in the case of negative emissions technologies (NETs). The study found that when people learned about NETs it changed their perception of the threat of climate change, leading to lower support for other mitigation initiatives.[90] Such possibilities should be considered and accounted for to the extent possible when modeling and evaluating mitigation opportunities and initiatives. Spillovers at every level, from household behavior to telecoupling across nations, deserve much more attention from the research community.[54] Spillovers can also be positive. An example is demonstration effects, where a successful implementation in one place encourages implementation in other places. Spillover effects likely vary across socioeconomic contexts and for different initiatives, technologies, and behaviors. Thus, we need a robust research literature to assess the impact of particular spillovers.

Table 2 illustrates initiatives to reduce GHG emissions from motor vehicle fleets by changing technology adoption, use, and maintenance. It indicates how TP and the elements of IF and BP could be calculated or estimated. Note that initiatives for technology adoption or use could be adopted and implemented by either governmental or non-governmental change agents. For replacement of internal combustion vehicles, illustrative initiatives include governmental fuel economy standards and private fleet operators deciding to switch to electric vehicles. The California Clean Vehicle Rebate Project is an example of a government initiative that seems to be successful. It offers rebates of

Table 2. Elements of the Tripartite Framework

	Mitigation Initiative	Technical Potential	Behavioral Plasticity		Initiative Feasibility	
			Adoption	Maintenance	Adoption	Implementation
Example: Technology uptake	*Regulatory:* fuel economy standard *Financial:* rebate for electric vehicle purchase *Behavioral:* improved fuel economy labeling	CO_2e reduction over lifetimes of all new vehicles under proposed initiative, compared with baseline	Estimated from data on uptake of technology or initiation of behavioral change by target actors under the most effective similar initiatives[15]	Estimated from data on maintenance of equipment or continuation of changed behavior under the most effective similar initiatives[15]	For public sector initiatives: estimated from public opinion data on the policy and expert assessment of lobbying power of interested and affected parties For private initiatives, estimated from expert assessment of market and social motivations and barriers	For regulations, estimated from judgment of regulators' motivations and ability to enforce;[91] for financial and behavioral, estimated from analysis of how well initiatives apply principles of best design[68]
Example: Use	*Regulatory:* carpool lanes *Financial:* lower mass transit fares *Behavioral:* dashboard fuel economy displays	CO_2e reduction over lifetimes of existing vehicles if maintained and used as intended under proposed initiative, compared with baseline				

Rows provide illustrations of how the concepts would be applied, and their magnitudes estimated for initiatives to reduce emissions from motor vehicle fleets.

up to $7,000 for the purchase or lease of a zero-emission or plug-in hybrid electric vehicle for individuals below a certain income cap and manufacturers' rebates for purchasers.

Initiatives and behavioral changes also have a time dimension. Reducing usage of GHG-emitting technologies and the frequency of other high-emitting actions (e.g., meat consumption, air travel) can affect emissions immediately. However, to keep those reductions in place, behavior changes have to be maintained and ideally become habitual.[86] Replacing existing equipment with new technologies can have more reliable impacts on a timescale of years to decades. Many norms that influence behavior could also change on that timescale. Transforming housing units, community geography, household sizes, or values to encourage adoption of new technologies or practices can yield long-term change but typically take multiple decades to implement at scale.[9] Such changes can be thought of as "locked in" over shorter time scales.[92] Analyses of the potential of initiatives with respect to an objective, such as limiting global warming to 2°C or 1.5°C must consider not only TP and the other factors that determine paths from potential to actual mitigation (IF and BP), but also the time scales to adopt and implement initiatives. This is the logic of the wedge approach, which assumes that the mitigation achieved by an initiative changes over time.

Some changes, even those that normally take several decades, can happen more rapidly when societal "tipping points" are crossed. These tipping points can occur in periods of generally perceived emergency but also when norms reach a moderate degree of consensus initiating further consensus, a norm cascade.[93] Tipping points effectively lock in changes in social-technical-institutional systems to alter the trajectory of GHG emissions in a lasting way.[92] Various plausible tipping points that could entrain processes to reduce GHG emissions have been identified,[70] but work is needed on the feasibility of implementing initiatives (IF) that might start tipping processes and the responsiveness of the targets of change (BP) to those initiatives once adopted.

INTEGRATING IF AND BP INTO POLICY ANALYSES

Identifying plausible scenarios of action at a regional, national, or local level demands unpacking the story of IF and BP. A central feature of IF and BP analyses are that they are inherently context dependent. An action, such as transitioning from single-occupant automobiles to mass transit or from internal combustion to electric vehicles, might be more easily influenced in places and times where certain social and cultural dynamics make targets of change more receptive to it. An initiative can affect BP by changing the convenience, attractiveness, cost, or belief in the effectiveness of a target action.[68] Over the intermediate term, the distribution of housing, employment, and other infrastructure is fixed, but initiatives can modify these over longer time periods. Both public and private initiatives that could expand BP might face greater barriers if they require large expenditures or threaten interest groups. Thus, achieving a mitigation objective will often require considering, and perhaps balancing, the characteristics that make initiatives feasible to adopt and implement (IF) and those that increase the response of target actors (BP).

An additional complexity is that actors who are sometimes targets of initiatives, such as individuals, households, and private businesses, can also be agents of change. For instance, individuals acting as citizens can affect IF for governments (e.g., through social movements); organizations can also do this as lobbyists, and they can influence other organizations by setting an example,[94] or creating pressure on how they procure supplies or make investments. Thus, they can affect IF for other change agents, and indirectly, BP, even for themselves. Social movements often take decades to achieve their goals, but sometimes this happens more quickly. Their direct and indirect influences within and across countries are the subject of an ongoing literature that could be used to better understand the dynamics of IF and BP.[95–98] Fully capturing these influences is challenging. At present, their effects might best be represented within scenarios of change (e.g., a scenario representing emissions change under a successful international social movement to reduce climate footprints).

Research into BP draws on empirical studies of behavior change[99–101] and established theoretical frameworks, such as the Theory of Planned Behavior,[102] Value Belief Norm Theory,[103] and Diffusion of Innovations Theory.[104] These and related theories are complementary; in most cases, each will add some insight into understanding behavioral change.[71,105,106] These approaches allow both qualitative and quantitative assessments and estimates of BP.[15] Such research has identified design principles for maximizing the effectiveness of initiatives aimed at changing behavior.[70,107–109]

As suggested above, research on IF draws on diverse scholarly traditions focused on adoption and implementation. Consideration of IF is needed for assessments to give realistic estimates of actual mitigation from initiatives. Even imperfect and uncertain analysis of IF can be useful, especially for identifying possible leverage points for action and areas where more research is needed. Even where estimates of IF remain largely qualitative, research on IF holds the promise of identifying best practices and design principles, just as qualitative research on BP has done. And it could be that models of disequilibrium and tipping points will prove helpful in understanding changes in IF.

Research on socio-technical transitions[37] can contribute to the assessment of IF and BP by providing insights into the ways that both can change over time. For instance, energy and transportation infrastructure is transformed as new technologies become available and are deployed, often in unexpected ways.[110] Rather than viewing changing infrastructure as driven either by technological innovation or by social change, a reasonable theory of socio-technical transition must consider a co-evolutionary process in which many actors try to shape the direction of the evolution.[111,112] This points to the possibility of self-sustaining paths by which adoption of emissions-reducing behaviors could raise both IF and BP and thus drive further adoption.

The co-evolution of social and technological change is illustrated by the transition of US consumers from incandescent to LED lighting. A combination of government regulations and private sector initiatives drove rapid technological advances in quality and price as well as extensive marketing to consumers. As high-quality bulbs became readily available at attractive prices, consumers embraced them, driving a virtuous circle in which growing demand supported further innovation and economies of scale in manufacturing, further raising quality and lowering prices. As a result, roughly two-thirds of general-purpose light bulbs sold in the United States are energy-efficient LEDs and per capita residential electricity consumption has fallen since 2010.[113,114] Furthermore, the embrace of LEDs by consumers, manufacturers, and retailers has changed the IF and BP landscape: the United States president has announced his intent to rescind regulations on light bulb efficiency, but manufacturers and retailers expect private sector actions to accelerate the market dominance of efficient LED bulbs even if the government withdraws the regulations.[115]

Another example is the transition from internal combustion to electric vehicles, which poses a greater socio-technical challenge: The interdependence of vehicle sales and charging infrastructure, combined with the behavioral differences between charging an electric vehicle and fueling an internal combustion vehicle and the psychology of attending to trip lengths and destinations that might be constrained by the need to recharge electric vehicles, produce more complex and less predictable dynamics in the interactions between the growth of the technological infrastructure and the public's embrace of that infrastructure.[37,116] Declarations by several national governments and large vehicle manufacturers and purchasers of their intent to rapidly transition from internal combustion to electric vehicles demonstrate significant IF in the public and private sectors. BP for widespread adoption by consumers remains uncertain,[117,118] but is likely to be affected by larger actors' choices, such as the placement of and access to charging stations and the motivations of car dealers to sell electric vehicles.[119] Critically, the mitigation achieved by this vehicle transition also depends on the transition from fossil fuels to other sources of electricity. A recent review of the literature on socio-technical transitions toward low-carbon energy systems concluded that there is great promise in the field, but many important challenges remain.[110] Other recent work demonstrates the promise of novel approaches, such as shared mobility platforms, to overcoming IF and BP barriers to the electrification of transport.[116]

SUGGESTIONS FOR INTEGRATION

Integrating IF and BP into policy analysis presents substantial challenges. We suggest three approaches. One is to continue and expand the tradition out of which the concepts of TP, IF, and BP grew: the analysis of climate mitigation wedges. Another is to focus primarily on using analyses of IF and BP in much the same manner as scenarios are currently used: as factors exogenous to IAMs that suggest contexts in which IAMs are deployed. The third approach is to integrate IF and BP more fully into the dynamics of IAMs.

Wedge analysis examines how to meet emissions reductions targets through a combination of existing technologies, including greater use of energy-efficient equipment, shifts toward decarbonizing energy sources, and development of carbon capture and storage, among others.[20] The basic premise is that climate stabilization can be achieved by dividing the difference between an emissions reduction objective and the expected trajectory from business-as-usual practices into stabilization wedges. Each wedge supposes that a particular mitigation opportunity can be realized over an extended period (e.g., 50 years) to achieve part of the intended mitigation. Each wedge represents the share of this mitigation that each opportunity can contribute.

The idea of a behavioral wedge[15] presumes that TP needs to be weighed by BP, to get a sense of the achievable mitigation from a technology or behavior, noting that BP is a function of how initiatives are designed and implemented, and IF, to represent the likelihood that such initiatives can be adopted and implemented. We suggest that careful analysis of various wedges that take account of TP and timing, part of the original wedge analysis, but also BP and IF, could provide more realistic assessments of specific pathways toward reaching a 1.5°C or 2°C objective. Such analyses, although less well-developed quantitatively than IAM-based analyses, could nonetheless be a useful complement to them. As with BP analysis, IF analysis could build on data from policies and programs already in place to estimate the adoption and implementation components. Integrating TP, IF, and BP estimates, and the effects of initiative implementation on BP can yield estimates of actual mitigation.[50,52,120–122]

As we have emphasized, research on IF and BP clearly indicates that these factors are context dependent.[123] Thus, using wedge analysis for global assessments will require the development and aggregation of analyses done for specific initiatives, specific target actors, and specific contexts (e.g., countries, policy contexts, urban versus rural locations, or income levels of target populations). The more quantitative research is available on context-specific IF and BP, the more effectively wedge analyses can be incorporated into globally aggregated quantitative models.

A logical opening for advancing the understanding of IF and BP and for taking a more explicit account of time horizons comes through the scenarios that frame IAM analyses. For example, the SSPs—a set of scenarios of future societal development—present possible trajectories or alternative futures involving demographics, human development, economy and lifestyles, policies and institutions, technology, and environment and natural resources.[124] In particular, the current SSPs span variation in consumption and diet, general environmental policy, and overall focus of policy and the strength of institutions. Analyses of IF and BP can be useful for assessing how likely different alternative mitigation futures might be and how to increase the likelihood of low-emission ones. Considering that SSPs are developed via expert elicitation, one early step might be to ensure that knowledge of IF and BP is included in the expertise base used to develop future scenarios, or alternatively that expert processes to assess IF and BP are input to SSP revisions. Social scientists engaged in the IPCC process could assess the IF of various initiatives (e.g., government policies, actions by industry groups, social movement activities) in various sectors (transport, buildings, etc.) and the BP of the initiatives' targets for bringing about SSPs that are desirable from the standpoint of limiting climate change. Such assessments can also point to directions for social scientists to conduct analyses that can support future IPCC efforts. Practitioners who work with potential change agents and targets of change can also help provide crucial expertise on IF and BP.

Formal inclusion of IF and BP into IAMs represents a greater challenge. It is difficult to see how they might become endogenous to the models. But other drivers are considered via scenarios influencing parameters within the model. We can imagine, for example, that estimates of the price elasticity of demand for renewable and energy-efficient technologies might be adjusted to reflect experience with typical, or highly effective, initiatives that encourage the adoption of those technologies. For example, the idea of increasing returns might be a vehicle for capturing some aspects of non-linear feedback.[125] And of course the models themselves are intended, in part, to influence initiative design and thus IF.

One approach to developing quantitative assessments of IF and BP, while accounting for spillovers, is to link survey and other empirical data to simulation. Of course, both the empirical data and the simulations need to be well grounded in theory if this line of analysis is to produce cumulative insights. For example, current understandings of the dynamics of policy networks and in particular of social learning in such networks might provide insights into IF in particular political contexts.[43,126–128] Similarly, linking survey data with agent-based or statistical simulation models could yield insights into BP and how initiatives might influence it.[43,129] The application of such tools to diverse types of agents and actions, in turn, should lead to improved understanding about how to deploy such approaches in ways that will be useful for policy analysis. And the requirements of modeling in the service of decision making would provide feedback that encourages theory to engage with decisions of great consequence and urgency.[40,130]

A special challenge will be to build cumulative knowledge by better integration of insights from public and elite surveys, survey-based experiments, quantitative and qualitative analysis of previous successes and failures in promoting and implementing initiatives, and theoretical analyses. For example, surveys and survey-based experiments can provide substantial insights into public acceptability of various types of initiatives and thus help guide initiative design. However, such results have to be integrated with an understanding of policy elites and the dynamics of policy networks.[57,59,131–135] The urgency of the problem underlines the need for a more integrated understanding that draws on and develops insights from diverse lines of research.

The kinds of analyses we are suggesting will be developed most effectively in deliberation with those in the public and private sectors, including NGOs, whose decisions will be shaped by the analysis. There is a tradition calling for linking scientific analysis to public deliberation that demonstrates the value of linked processes.[135] It can also provide guidance as to how to design such processes.[136]

CONTRIBUTION OF THEORETICAL FRAMEWORK

The development and refinement of IAMs have proven and will continue to prove very important to decision making around climate change. IAMs provide useful estimates of the magnitude of mitigation required to reduce risk and, under conventional assumptions of welfare economics, the costs associated with those options. Within the limits of those assumptions, they are very helpful in sorting through strategies and eliminating those that seem either unlikely to provide the desired level of risk reduction or that will do so only at high economic costs.

We believe, however, that the ability of IAMs to improve decision making can be enhanced by incorporating into the modeling process a broader array of insights about pathways from opportunities and initiatives to actual mitigation. In particular, we emphasize the value of consideration of IF, that is of adoption and implementation with special attention to differences in feasibility across change agents and jurisdictions. An otherwise very promising strategy that has little chance of being implemented globally, or even in some nations that are major GHG emitters, might be less effective than a standard IAM analysis suggests. Because many initiatives require responses by a diversity of individuals, households, and organizations, realistic estimates of actual mitigation also require consideration of BP. Analyses of the economic implications of a climate change mitigation initiative are necessary but not sufficient to fully estimate actual mitigation impact or to assess which initiatives to pursue.

The goal of climate change mitigation initiatives is to reduce risk globally. Risk reduction can sometimes be achieved by pursuing mitigation opportunities that have only modest TP, and so do not appear "best" when compared with higher TP ones. Such opportunities might still be desirable targets to pursue when IF and BP are sufficiently large: that is, initiatives to pursue them have a strong likelihood of being enacted and implemented and they are likely to bring about substantial behavioral change.[19]

Finding ways to build the tripartite framework into the modeling and initiative assessment process will also help hone the science. Ongoing dialogue between the IAM community and those scientists examining the determinants of individual, organizational, and policy actions will sharpen the questions asked by the latter community, encouraging cross-disciplinary work. Of particular importance will be analyses that account for how actors are embedded in social networks, and of differences across contexts, including across nations and non-governmental actors within a nation. This will yield a more theoretically integrated and methodologically catholic science for assessing potential mitigation initiatives and informing change agents seeking effective climate mitigation strategies.

CONCLUSION

Integrating all of the relevant sciences needed to advance analyses of opportunities to reduce climate footprints will undoubtedly be a major task. A great deal of research on IAMs has improved understanding of how various initiatives might promote mitigation objectives and can inform choices of initiatives and ways to implement them. However, we need to deepen our understanding of what the IPCC[1] refers to as feasibility. The tripartite conceptual framework offered here unpacks the feasibility concept in ways that point to key research needs and opportunities for integrating the sciences that examine the various elements of feasibility with the sciences that have so far contributed to IAMs. We have also suggested how the sciences of feasibility might be deployed, minimally in parallel with, but possibly as input into, IAMs. We offer this framework as an example of how to proceed in integrating the sciences. The challenge of stabilizing climate at acceptable risk levels is formidable, and we are more likely to understand pathways to change and make wise choices to minimize risks if we make the best use possible of all relevant science.

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AUTHOR CONTRIBUTIONS

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