CellPress

One Earth

Perspective

A method to identify barriers to and enablers of implementing climate change mitigation options

Linda Steg,[1,*] Janet Veldstra,[1] Kiane de Kleijne,[2] Şiir Kılkış,[3] André F.P. Lucena,[4] Lars J. Nilsson,[5] Masahiro Sugiyama,[6] Pete Smith,[7] Massimo Tavoni,[8] Heleen de Coninck,[2,9] Renée van Diemen,[10] Phil Renforth,[11] Sebastian Mirasgedis,[12] Gregory Nemet,[13] Robert Görsch,[1] Helene Muri,[14] Paolo Bertoldi,[15] Luisa F. Cabeza,[16] Érika Mata,[17] Aleksandra Novikova,[18] Lucas R. Caldas,[19] Marta Chàfer,[20] Radhika Khosla,[21] and David Vérez[22]

[1]Environmental Psychology, Faculty of Behavioral and Social Sciences, University of Groningen, Groningen, the Netherlands
[2]Department of Environmental Science, Radboud Institute for Biological and Environmental Sciences, Radboud University Nijmegen, Nijmegen, the Netherlands
[3]TÜBİTAK, The Scientific and Technological Research Council of Turkey, Ankara, Turkey
[4]Center for Energy and Environmental Economics (Cenergia), Energy Planning Program (PPE), COPPE, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil
[5]Department of Technology and Society, Lund University, Lund, Sweden
[6]Institute for Future Initiatives, The University of Tokyo, Tokyo, Japan
[7]Institute of Biological and Environmental Sciences, University of Aberdeen, Aberdeen, UK
[8]Politecnico di Milano and RFF-CMCC European Institute on Economics and the Environment, Centro Euromediterraneo sui Cambiamenti Climatici, Milano, Italy
[9]Industrial Engineering and Innovation Sciences, Eindhoven University of Technology, Eindhoven, the Netherlands
[10]Centre for Environmental Policy, Imperial College London, London, UK
[11]Research Centre for Carbon Solutions, Heriot-Watt University, Edinburgh, UK
[12]Institute for Environmental Research & Sustainable Development, National Observatory of Athens, Athens, Greece
[13]La Follette School of Public Affairs, University of Wisconsin-Madison, Madison, WI, USA
[14]Industrial Ecology Program, NTNU, Torgarden, Norway
[15]European Commission, Joint Research Centre, Ispra, Italy
[16]GREiA Research Group, University of Lleida, Lleida, Spain
[17]IVL Swedish Environmental Research Institute, Östersund, Sweden
[18]Institut für Klimaschutz, Energie und Mobilität (IKEM), Berlin, Germany
[19]Faculdade de Arquitetura e Urbanismo, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil
[20]Department of Computer and Industrial Engineering, Universitat de Lleida, Lleida, Spain
[21]Smith School of Enterprise and the Environment, School of Geography and the Environment, University of Oxford, Oxford, UK
[22]GREiA Research Group, University of Lleida, Lleida, Spain
*Correspondence: e.m.steg@rug.nl
https://doi.org/10.1016/j.oneear.2022.10.007

SUMMARY

Mitigation option are not yet being implemented at the scale required to limit global warming to well below 2°C. Various factors have been identified that inhibit the implementation of specific mitigation options. Yet, an integrated assessment of key barriers and enablers is lacking. Here we present a comprehensive framework to assess which factors inhibit and enable the implementation of mitigation options. The framework comprises six dimensions, each encompassing different criteria: geophysical, environmental-ecological, technological, economic, sociocultural, and institutional feasibility. We demonstrate the approach by assessing to what extent each criterion and dimension affects the feasibility of six mitigation options. The assessment reveals that institutional factors inhibit the implementation of many options that need to be addressed to increase their feasibility. Of all the options assessed, many factors enable the implementation of solar energy, while only a few barriers would need to be addressed to implement solar energy at scale.

INTRODUCTION

Climate change is one of the most challenging problems the world is facing today.[1] Average global surface temperature has already increased by 1.1°C compared with pre-industrial times, which has resulted in more extreme weather events (e.g., heat waves, floods, droughts), reductions in global food supply, and increased mortality rates.[1,2] The negative impacts of climate change are expected to become more severe if global surface temperatures continue to increase. To prevent this global crisis, in 2015, 196 parties signed the Paris Agreement and committed to the goal of limiting global warming to well below 2°C, and preferably to 1.5°C, compared with pre-industrial times. At COP26, parties agreed to accelerate action on climate this decade in the Glasgow Climate Pact.

Many options in different sectors have been identified that would contribute to limiting climate change by reducing greenhouse gas emissions. We define mitigation options as technologies or practices that reduce greenhouse gas emissions or enhance sinks.[3] These include renewable energy sources, electrification, energy and fuel efficiency measures, demand reduction (e.g., reduce the use of motorized transport, home energy savings), dietary changes (i.e., less animal protein consumption), and low- or zero-energy buildings. In addition, achieving net-zero greenhouse gas emissions would require the implementation of carbon dioxide removal (CDR) approaches (e.g., afforestation, direct air carbon capture and storage, enhanced weathering) to counterbalance any residual greenhouse gas emissions.[1] Although a range of mitigation options are being implemented in different regions (e.g., solar photovoltaics [PVs], wind farms, electric vehicles), mitigation options are not yet being implemented at the scale required to limit global warming in line with the Paris Agreement's long-term temperature goal. In fact, carbon emissions are still increasing after a brief drop in 2020, despite the COVID-19 pandemic.[2–4] It is therefore critical to understand which factors affect the likelihood of promising mitigation options being implemented at scale and to identify which barriers would need to be overcome to promote their rapid and widespread implementation.

A wide range of factors may inhibit the implementation of mitigation options. For example, large-scale generation of bioenergy faces legal and institutional barriers[5–8] and exerts pressure on land use that is difficult to reconcile with planetary boundaries.[9,10] The production of biomass can also compete with food production[11] and may contribute to water scarcity.[12] Electric mobility and electricity storage rely on scarce geophysical resources,[13,14] and low-emission aviation and shipping is technologically challenging.[15–17] International competition is a challenge for decarbonizing the production of emission-intensive basic materials, since such production typically entails higher production costs.[18–20] Carbon capture and storage is logistically challenging[21,22] and is generally not supported by the public.[23–26] Similarly, technological CDR options may not be accepted by the public,[26,27] and most technological CDR options are not yet technologically mature.[3,28] In many countries, people are reluctant to fly less[29] and to reduce meat consumption[30,31] and have negative attitudes toward vegetarian food and meat substitutes,[32,33] which may explain why global meat consumption has continued to increase rather than decrease.[34] Furthermore, increasing nuclear generation capacity is significantly costly and associated with high investment risks, and regulatory, political, and management contingencies cause delays in reactor construction.[35] Nuclear power also faces public resistance[36–38] and causes intergenerational inequity.[39] Improved biomass-burning cookstoves have limited, and lower than expected, impacts on improving energy access and reducing greenhouse gas emissions, as households tend to use these stoves irregularly and inappropriately and fail to maintain them, and their usage declines over time.[40–43] Hence, a multitude of factors may inhibit the feasibility of implementing different mitigation options.

At the same time, various factors can enable the implementation of mitigation options and can support the realization of their full mitigation potential. For example, a shift to non-motorized transport not only would limit climate change, but also is a cost-effective option, enhances equity, and yields various co-benefits, such as improved health and increased public space.[13,44] Furthermore, renewable energy technologies, such as solar and wind, create employment[45] and can reduce environmental problems such as air pollution and toxic waste.[46] Moreover, solar PVs are an economically viable option,[47,48] are not likely to compete strongly with food production,[49] have a high technical potential,[48,50,51] and are generally widely supported by the public.[52–56] Further, increased materials efficiency and circularity reduces pressure on primary resources, while electrification of industry reduces air pollution from fuel combustion.[57] Forward-looking businesses are exploring reliable CDR options, creating momentum for the nascent industry.[58] Also, improved energy performance of buildings can benefit health and well-being by alleviating fuel poverty, reducing fuel consumption and associated financial stress, and improving ambient air quality.[59–72] Yet, such enabling factors, even when identified and available, are not always utilized to support mitigation efforts, representing an underutilized opportunity.

Mitigation options are more likely to be implemented when critical barriers are removed and when efforts are made to bring factors enabling their implementation into play. Notably, many enabling factors imply that mitigation options have co-benefits, which may in some cases compensate for negative impacts of mitigation options, or even remove some barriers. For example, public support may increase if people believe that mitigation options have more favorable environmental outcomes, even when such options are associated with some costs.[73–75]

In sum, a wide range of factors has been identified that affect the likelihood that mitigation options will be implemented. Yet, the literature is scattered, and a systematic and integrated assessment of key barriers and enablers is lacking. Such an integrated assessment is critical to understand whether, when, and how relevant mitigation options can be implemented at scale and which barriers and enablers would need to be targeted to enhance their feasibility. Notably, establishing and strengthening a given enabling factor or removing a particular barrier to implementing a mitigation option would have limited or even no effects if other important barriers are overlooked. Hence, a comprehensive overview of relevant barriers and enablers is critical to identify which policies and changes could enhance the overall feasibility of mitigation options by removing key barriers and establishing and strengthening key enablers of their implementation.

In this paper, we aim to introduce a comprehensive framework for understanding the feasibility of mitigation options that was developed and used in the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report.[3] We will illustrate how the framework can be employed by assessing the feasibility of some mitigation options in different sectors and systems. We do not aim to provide a comprehensive overview of the feasibility of a wide range of mitigation options, but rather to demonstrate how the feasibility assessment framework can be used. Our assessment reveals that, currently, many factors enable the implementation of mitigation options, but that significant policy efforts are needed to address different barriers so that mitigation options can be employed at scale. In particular, institutional factors inhibit the implementation of many options and need to be

Table 1. Dimensions and indicators for assessing the barriers to and enablers of implementing mitigation options

Dimension	Indicators
Geophysical feasibility: availability of required geophysical resources	physical potential: extent to which there are physical constraints to implement the option
	geophysical resource availability (including geological storage capacity): availability of resources needed to implement the option (e.g., minerals, fossil fuels)
	land use: claims on land when implementing the option
Environmental-ecological feasibility: impacts on the environment	air pollution: changes in air pollutants, such as NH_4, CH_4, fine dust
	toxic waste, ecotoxicity, and eutrophication
	water quantity and quality: changes in amount of water available for other uses, including groundwater
	biodiversity: including changes in area of conserved primary forest or grasslands that affect biodiversity and management aimed at conservation and maintenance of land carbon stocks
Technological feasibility: extent to which the required technology can be implemented at scale quickly	simplicity: is the option technically simple to operate, maintain, and integrate
	technology scalability: can the option be scaled up quickly to a meaningful level
	maturity and technology readiness: R&D (and time) needed to implement the option
Economic feasibility: financial costs and benefits and economic effects	costs now, in 2030, and in the long term, including investment costs (investments per ton CO_2 avoided), costs in USD/tCO_2-eq, and hidden costs
	effects on employment and economic growth
Sociocultural feasibility: public engagement and support, and health, well-being, and distributional effects	public acceptance: the extent to which the public supports the option and will change their behavior accordingly
	effects on health and well-being (excluding environmental-ecological impacts)
	distributional effects: equity and justice across groups, regions, and generations, including security of energy, water, and food and poverty eradication
Institutional feasibility: institutional capacity, governance structures, and political support	political acceptance: extent to which politicians and governments support the option
	institutional capacity and governance, cross-sectoral coordination: capability of institutions to implement and handle the option, and coordinate it with other sectors, stakeholders, and civil society
	legal and administrative capacity: extent to which supportive legal and administrative changes can be achieved

addressed to increase their feasibility, while technological and economic barriers are generally less prominent. The feasibility assessment provides critical information to governments and decision makers on what factors would need to be targeted to improve the feasibility of options to ensure that options can be implemented at scale on a timely basis.

FEASIBILITY ASSESSMENT FRAMEWORK

We first developed a theoretical framework that would guide the feasibility assessment, extending the feasibility assessment framework employed in SR1.5.[1] The feasibility assessment framework comprises six dimensions that can affect the feasibility of implementing mitigation options in different sectors and systems: geophysical, environmental-ecological, technological, economic, sociocultural, and institutional feasibility. For each dimension, experts that contributed to Working Group 3 of AR6[3] identified a key set of indicators that can inhibit or promote the implementation of mitigation options (see Table 1). The experts covered all required expertise, such as detailed knowledge of the relevant feasibility dimensions (e.g., expertise on environmental and ecological systems, economic factors, sociocultural factors, or institutional factors) and detailed knowledge of the relevant sectors or systems (e.g., energy, transport, industry, urban).

Geophysical feasibility reflects whether geophysical resources needed to implement a mitigation option are available or secured. The geophysical feasibility of an option depends on whether there are physical constraints to implementing an option (e.g., availability of water flow to produce hydroelectric power), the availability of resources to implement the option (e.g., geological storage capacity for carbon capture and storage), and the availability of land to implement the option (e.g., to grow terrestrial biomass feedstocks for bioenergy or biochar production).

Environmental-ecological feasibility reflects the extent to which mitigation options would have positive or negative impacts on the environment. Some scholars have critiqued the inclusion of environmental-ecological feasibility, arguing that it is more closely linked to desirability.[76] We included it, as we are aiming to identify which barriers would need to be addressed to enhance feasibility (and not whether an option is feasible at all), and all other things being equal, mitigation options are more likely to be implemented if they have positive environmental-ecological impacts (in addition to mitigating climate change), while feasibility is constrained when options have negative environmental-ecological impacts. Four critical indicators to assess the environmental-ecological feasibility of options are included in the assessment: impacts on air pollution; toxic waste, ecotoxicity, and eutrophication; impacts on water quantity and quality; and impacts on biodiversity.

Technological feasibility reflects the extent to which the required technology can be implemented at scale, quickly. The technological feasibility is assessed on the basis of the following three indicators: whether the option is simple to operate, maintain, and integrate; whether the option can be scaled up rapidly; and the technological readiness level of the option.

Economic feasibility reflects the financial costs and benefits and the economic effects of mitigation options. Two indicators reflect the economic feasibility: how costly it is to implement the option, in both the short and the long term, and the effects on employment and economic growth. We included the effects on economic growth as an indicator as this is still a major concern in current economic models and political landscapes in most countries. Yet, some scholars have critiqued the paradigm of economic growth, arguing that global consumption and production need to reduce to achieve a socially just and ecologically sustainable society.

Sociocultural feasibility reflects whether required levels of public engagement and support can be secured and the social impacts of implementing the option. Three indicators are assessed that reflect the sociocultural feasibility. First, an option is more feasible when the public supports the option and is willing to change its behavior accordingly (e.g., by adopting and using the relevant option). Second, sociocultural feasibility is enhanced when an option has positive (rather than negative) impacts on human health and well-being. Third, options are more feasible and acceptable if they enhance equity and justice, reduce poverty, and secure access to energy, water, and food for all.[73,77]

Institutional feasibility reflects whether the required institutional capacity, governance structures, and political support are in place. Institutional feasibility depends on political support for the option; institutional capacity and governance to coordinate, implement, and handle the option; and the legal and administrative capacity needed to implement and manage the option.

FEASIBILITY ASSESSMENT APPROACH

Our feasibility assessment framework provides a multidimensional approach to systematically assess the feasibility of implementing different mitigation options. The first step in the feasibility assessment comprises selecting options that would mitigate climate change in different sectors globally, including supply-side options (e.g., hydro energy, sustainable forest management, changes in building construction, carbon capture and storage) as well as demand-side options (e.g., changes in diets, reductions in motorized travel). Given the urgency to mitigate climate change, we selected options that have a relatively high mitigation potential when employed at scale (as assessed in AR6[3]) and options that play a prominent role in mitigation scenarios and pathways and thus likely need to be implemented to limit global warming to well below 2°C: solar energy; integrating sectors, strategies, and innovations in urban systems; envelope improvement of buildings; electric vehicles for transport; electrification in industry; and enhanced weathering. When possible, we indicate the level of deployment of the given option in the mitigation pathways reviewed in AR6 of the IPCC (publicly available at https://data.ece.iiasa.ac.at/ar6/#/login). Specifically, we report the expected development of specific options over the next decades across 300 scenarios that are compliant with the Paris Agreement, that is, with end-of-century temperatures below 1.5°C or 2°C (categories C1-C2-C3 in the IPCC report).[3] The option "integrating sectors, strategies and innovations in urban systems" is not included in the scenario database, as it is a very general option, but considered to be important in urban emission scenarios.[78] Enhanced weathering is included in only a few scenarios, making an assessment unreliable. Therefore, we do not indicate the level of deployment in Paris-compliant scenarios for these two options.

Next, for each option, experts involved in AR6 evaluated the extent to which the feasibility indicators listed in Table 1 would inhibit or enable the implementation of that option in general, at a global level, based on the literature. Specifically, for each option, it was assessed whether an indicator would generally have a positive or negative impact, or have both positive and negative impacts, on the feasibility of implementing the option. The latter may occur when the impact of the indicator depends on context, region, scale, and time of implementation. For example, the literature indicates that the physical potential of hydroelectric power is high in regions with abundant water, but low in water-scarce regions, and bioenergy will become less feasible when employed at a very large scale, as this would compete with food production. Alternatively, studies have shown that options can have mixed positive and negative impacts for a given indicator. For example, improvement of the envelope of buildings may improve health through better air quality, alleviate fuel poverty, and mitigate heat island effects, but may at the same time cause sick-building syndrome symptoms when ventilation is inadequate.[60,62,64,68,70,72,79–83] In sum, the following scores were used in the assessment (cf. Nilsson et al.[84]) to systematize the multidimensional assessment:

- The (−) reflects that the indicator poses a barrier to implementing the option, e.g., it is associated with high costs, pollution, or land use or low public or political acceptance.
- The (±) reflects that the indicator can both enable and inhibit the implementation of the option, e.g., it requires more land use in some regions, but less land in other regions.
- The (+) reflects that the indicator enables the implementation of the option, e.g., it is associated with low costs, little pollution, limited land use, or high public or political acceptance.

The experts acknowledged that some indicators may not be applicable for an option or may not affect the feasibility of the option (coded as 0). For example, demand-side mitigation options typically do not rely on geophysical resources, and restoring

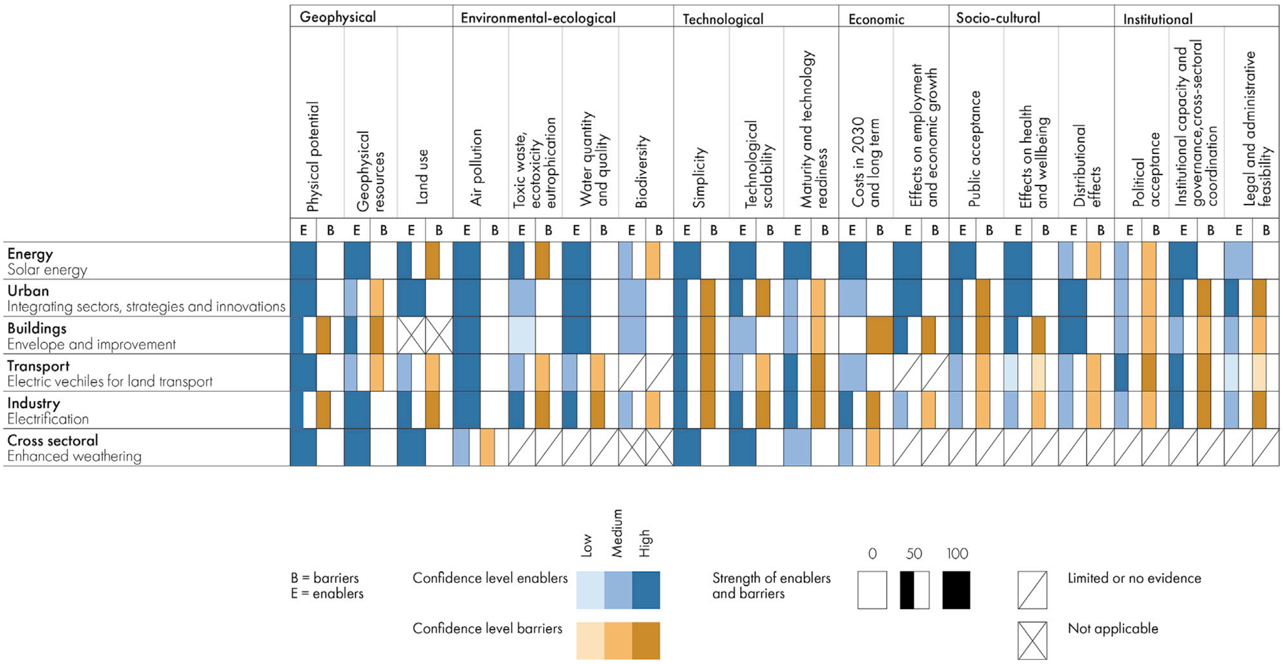

Figure 1. The extent to which different factors would enable or inhibit the deployment of selected mitigation options in different sectors and systems

Blue bars indicate the extent to which the indicator enables (E) the implementation of the option and brown bars indicate the extent to which an indicator is a barrier (B) to the deployment of the option, relative to the maximum possible barriers and enablers assessed. An X signifies the indicator is not applicable or does not affect the feasibility of the option, while a forward slash indicates that there is no or limited evidence for whether the indicator affects the feasibility of the option. The shading indicates the level of confidence, with darker shading signifying higher levels of confidence.

forests and other ecosystems is not associated with toxic waste, ecotoxicity, and eutrophication.

To enhance robustness, transparency, and reproducibility, the feasibility assessment is based on different strands of literature. Moreover, the level of confidence in the assessment is indicated (low, medium, or high) and reveals the robustness and agreement of the evidence provided in the literature. In case the literature provides no or limited evidence on the extent to which a given indicator would inhibit or enable the deployment of the option, no assessment is provided. Rather, it is indicated that the evidence base is limited or lacking, coded as limited evidence (LE) and no evidence (NE), respectively, signaling key knowledge gaps that need to be addressed in future research.

The literature indicates that the feasibility of options can vary across contexts (e.g., region), scale (e.g., small- versus large-scale deployment of the option), and time of implementation (e.g., 2030 versus 2050). For example, studies have shown that low-carbon construction materials can be scarce in some regions,[85,86] energy-intensive industry may relocate to regions with bountiful solar and wind resources,[87,88] financial and institutional barriers to scaling up PV deployment are mostly prominent in developing countries,[89,90] and maturity and technology readiness level varies for different parts of the supply chain of hydrogen fuel cell vehicles for land transport.[91–93] Therefore, Table S1 indicates whether and how the impact of an indicator on the feasibility of the option varies across context (including region), scale, and time.

Figure 1 illustrates the outcomes of the assessment of the feasibility of selected mitigation options from different sectors and systems, indicating which factors affect their feasibility. This is complemented by Table S1, which indicates whether the effect of the indicator on feasibility of the options differs across context, time, and scale. Table S1 also displays the literature on which the assessment is based; therefore, we do not repeat the references in the text below. Figure 1 and Table S1 aim to demonstrate how to employ the feasibility assessment framework, rather than comparing the feasibility of a comprehensive set of mitigation options.

Solar energy plays a major role in essentially all of the Paris-compliant scenarios, with a mean electricity generation in 2050 of around 25 (interquartile range: 17–28) times current levels. This major deployment is due to the high competitiveness and matureness of solar power, which is already cost competitive today with fossil fuels and whose costs are expected to further decline. Figure 1 shows that many factors generally enable the implementation of solar energy. Notably, solar energy is economically and technologically viable and faces few sociocultural and institutional barriers in many countries. Specifically, solar energy is generally supported by the public and has positive impacts on human health and well-being. Yet, high upfront costs may deter adaption of solar PVs for low-income groups and developing countries. In most jurisdictions, solar energy has overcome institutional, legal, and administrative challenges posed by vested fossil fuel interests, but political acceptance is low in some cases. Although solar creates many environmental benefits by displacing fossil fuels, it uses substantial land and consequently can threaten biodiversity in some (protected) areas and can compete with agriculture and the built environment in densely populated areas. At the end of their useful life, solar PV panels can contribute to material waste, some of which may be toxic, but this can be avoided by recycling the material, which is mostly glass and easily repurposed. Overall, the assessment indicates that solar is a feasible option across almost all dimensions but that care should be taken to remove or reduce some barriers, specifically related to land use, distributional effects, recycling, and, in some cases, lack of political support.

In urban systems, integrating sectors, strategies, and innovations, particularly urban land use and spatial planning for walkable and co-located densities together with electrification of the urban energy system, has mostly beneficial environmental effects, as it also reduces other environmental problems, including air quality, and reduced pressures on land use and carbon sinks due to compactness. The option also has beneficial impacts on the economy, which would support the deployment of this option at scale. However, there are some technological barriers that need to be addressed, such as increasing complexity and reduced levels of simplicity when there is a need for integrated urban planning and the use of electrified urban infrastructure to support demand response in the energy system. There are also scalability issues due to existing urban forms being a barrier to change. Public acceptance may be limited if urban inhabitants are not involved or made aware of the co-benefits of this option. Most importantly, various institutional barriers would need to be addressed to enhance the feasibility of this option. Notably, integrated action requires significant efforts for coordination across multiple sectors in tandem, and institutional capacity, if not strengthened to a suitable level to handle this process, can remain short of the efforts this entails. The assessment indicates that targeted and coordinated policy efforts are needed to remove the various barriers, to ensure that this option can be implemented at scale, and to bring into play the different enabling conditions, including the formation of partnerships, to be able to support ambitious mitigation efforts.

Energy efficiency improvements in buildings are an important decarbonization option for attaining climate stabilization. The global final energy in residential and commercial buildings in Paris-consistent scenarios is only moderately higher in 2050 than today (mean, +9.4%; interquartile range, −1% to +16%); this reflects an assumption about efficiency improvements in buildings when accounting for the increasing energy needs of developing countries. Figure 1 reveals that envelope improvement in buildings currently faces different types of barriers, including the use of resources, since conventional insulation materials to a large extent are derived from petrochemicals, and more research is needed to develop sustainable materials. Also, this option may not be easily applicable to historical and heritage buildings, where modifications to façade are restricted. Moreover, some envelope improvements lack public support, as they are not perceived as a priority for energy-efficiency policies, particularly in warm climates and in developing countries. When poorly planned and with inadequate ventilation, building-envelope improvement may have negative effects on health and well-being. In addition, this option faces some technological barriers, as some solutions are still under development and rather complicated to implement, especially when requiring retrofits, and technological scalability is to some extent limited by buildings' stock lock-in. At the same time, Figure 1 indicates that building-envelope improvement would mostly reduce other environmental problems as a result of the reduced consumption of natural resources and reduced air pollution levels. Also, efficient building envelopes can result in lower energy bills, helping to alleviate energy and fuel poverty and improving energy security. Furthermore, building-envelope improvement generally is an economically viable option and would enhance equity and justice across groups. Nevertheless, long payback time, energy price dynamics, discount rates, and split incentives may be barriers affecting envelope improvement decisions.

Many Paris-compliant scenarios assume wide-scale adoption of electric vehicles for transport. The share of electricity in final energy for transportation is expected to increase by a factor of 10 (range: 6–13) over the next three decades globally, reflecting the technological maturity and competitiveness of electric vehicles, which can be observed already today. Various factors enable the deployment of electric vehicles for land transport in many regions, including sufficient physical potential, reductions in air pollution, and low economic costs. These factors could be brought into place to enhance the rapid wide-scale deployment of electric vehicles. At the same time, different barriers would need to be addressed, including toxic waste, especially in relation to the batteries (when considering life-cycle impacts), which could be achieved by replacing toxic components with less damaging materials, improved recycling of batteries, safer disposal methods, and improved governance for the mining and production of key minerals. While light-duty electric vehicles are generally technologically mature and scalable, long-haul and heavy-duty vehicles still face technological barriers, requiring improved charging infrastructures and electric grid coordination in some regions. Moreover, public and political support, as well as the institutional, legal, and administrative capacity to support electromobility, would need to be enhanced in some regions. High upfront costs of electric vehicles may raise equity concerns,[94,95] but operation costs may decrease due to the high efficiency of electric vehicles.

The share of electricity in final energy use in industry is likely to increase in Paris-compliant scenarios (mean increase by 2050, 2; range, 1.75–2.5), although this remains the sector where (decarbonized) fuels continue to play a role given the need for high temperatures. Electrification of industry, including direct and indirect (e.g., with hydrogen) electrification, is an option that clearly illustrates how feasibility can vary across context, scale, and time. Light industry and manufacturing can easily switch to electricity for most process needs, whereas electrification of energy- and emissions-intensive industry is more challenging.[18,96] The complexity and heterogeneity of heavy industry mean that the role and maturity of electrification options vary across subsectors, but increased production cost is a common feasibility challenge.[97] For example, hydrogen direct reduction (HDR) steelmaking, which was not considered feasible only 5–7 years ago, now seems highly feasible, and numerous steel companies have announced HDR initiatives in 2020 and 2021 (see https://www.industrytransition.org/green-steel-tracker/).

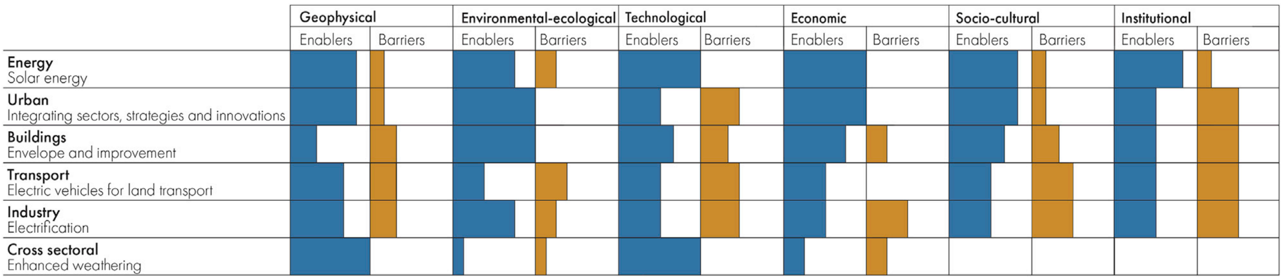

Figure 2. Geophysical, environmental-ecological, technological, economic, sociocultural, and institutional factors that can enable or act as barriers to the deployment of mitigation options

Blue bars indicate the extent of enablers of deployment within each dimension. This is shown relative to the maximum number of possible enablers (the blue and white bars combined). Brown bars indicate the extent of barriers to deployment within each dimension. This is shown relative to the maximum number of possible barriers (the brown and white bars combined). The blue and brown bars may not add up to 100% because some indicators are not applicable to the option or because of limited or no evidence on the extent to which relevant indicators affect the feasibility of the option (see Figure 1).
© Leah Rangi.

There are also signals that the market, notably automakers, is willing to pay the price premium.[98] While this can be achieved with an increase in global electricity demand of a few thousand terawatt hours, the electrification of primary plastics production may require 10,000 TWh (~40% of current global demand) or more, indicating the different scales involved, which has implications for their feasibility.[99,100] Also, the plastics and petrochemical sectors do not yet seem to consider decarbonization as a feasible prospect in light of their heavy investments in conventional production capacity and how they proliferate unsustainable markets.[101,102]

A range of factors would enhance the implementation of enhanced weathering (i.e., removing carbon dioxide by spreading large quantities of selected and finely ground rock material onto extensive land areas, beaches, or the sea surface), including the availability of required geophysical resources and land and the simplicity and scalability. At the same time, enhanced weathering is relatively costly and causes air pollution, which would need to be addressed to enhance its feasibility. Yet, as this is a relatively novel mitigation option, many knowledge gaps have been identified with regard to the feasibility of deploying enhanced weathering, which need to be addressed in future research to better understand (ways to enhance) its potential.

Figure 1 provides an assessment of the feasibility of mitigation options across the six dimensions. Table S1 shows that the enablers of and barriers to the implementation of most of the options vary across regions, scales, and time. Importantly, most options face barriers when they are implemented at a large scale, although the scale at which barriers manifest themselves varies across options. Future research can study the reasons for such differences in more depth, which may reveal important insights into how to improve the feasibility of options more broadly.

Figure 1 provides a detailed overview of relevant barriers and enablers of the deployment of mitigation options in general, and Table S1 indicates the extent to which these vary across context, scale, and time, giving clear guidelines on which barriers could be addressed to improve the feasibility of options. At the same time, the information provided may be somewhat overwhelming. To provide a first general understanding of the feasibility of options that is easier to grasp, the assessments can be aggregated across the six dimensions (see Figure 2). To do so, we counted a minus score as two minus points, a plus score as two plus points, and a plus-minus score as one minus and one plus point. Next, we computed the total number of minus and plus points for each dimension-option combination, relative to the maximum possible score per dimension for each option. The resulting scores represent the extent to which each feasibility dimension enables or constrains the deployment of the relevant mitigation option.

Figure 2 enables one to see at a glance which options can be readily implemented and which factors would need to be targeted to improve the feasibility of options that face implementation barriers. This figure helps to identify options and dimensions where policy efforts are most urgently needed. For example, Figure 2 indicates that more policy efforts are needed to enhance the feasibility of envelope improvement, while less effort is needed to address feasibility challenges for deploying solar energy. Moreover, Figure 2 indicates that efforts are particularly needed to remove institutional barriers that inhibit the deployment of mitigation options, while technological and economic barriers are generally less prominent. Since institutional barriers could likely dominate other factors, major government policies may be needed to remove different barriers, such as laws and pricing instruments. This makes it even more critical to understand how institutional barriers can best be reduced or removed, which factors promote institutional change, and how to remove barriers (e.g., powerful lobbies) to the implementation of major new climate mitigation policies.

DISCUSSION

The feasibility assessment framework aims to address important policy-relevant questions around what factors affect the implementation of mitigation options, which is critical to understand the extent to which options can achieve their full mitigation potential. Specifically, the feasibility assessment framework can be employed to identify which barriers would need to be overcome and which enabling factors would need to be put into place to enhance the likelihood that options can be deployed at scale. The mitigation potential of options is not part of this framework. Yet, given the urgency of mitigating climate change, the feasibility assessment would ideally be employed to assess options with a relatively high mitigation potential when employed at scale and options that play a prominent role in mitigation scenarios and pathways and thus likely need to be implemented to limit global warming to well below 2°C.

Our feasibility framework extends on earlier frameworks by including a wider range of factors that affect the feasibility of mitigation options (see Table 1) across different sectors and systems. For example, Jewell and Cherp[76] consider the economic and political feasibility of mitigation options, whereas Nielsen and colleagues[103] propose that institutional feasibility (i.e., the likelihood that governments will support the implementation of the mitigation option) and social feasibility (i.e., expected changes in demand when the option would be implemented) affect the realistically achievable mitigation potential of options. Yet, both frameworks overlook other feasibility dimensions, such as the availability of geophysical resources and wider environmental impacts of mitigation opportunities that can be critical barriers to or enablers for implementing options. They also do not systematically consider economic and technological factors that may enable or constrain the implementation of mitigation options. Further, we extend previous studies that assessed co-benefits and trade-offs of mitigation options[104,105] by identifying key factors that inhibit or enable the deployment of mitigation options.

Moreover, the feasibility framework by Nielsen and colleagues[103] primarily aims to assess the actual mitigation potential of options and the initiatives aimed at achieving them, by considering the extent to which options will be adopted and used as intended. In contrast, we aim to identify which factors affect the likelihood that options will be implemented at scale in the first place and which barriers would need to be removed to make sure that mitigation options can and will be implemented at scale.

We also extend and improve a first attempt of the IPCC to assess the feasibility of mitigation and adaptation options employed in the Special Report on Global Warming of 1.5°C.[1,106] Notably, in SR1.5, the feasibility assessment aimed to identify barriers to the implementation of options. We extended this approach by also assessing which factors would enable their implementation. The latter reveals potential co-benefits of options, which may increase the likelihood that they are rapidly implemented at scale. For example, low costs and high levels of public support can enable and accelerate the implementation of solar PVs.[47,54,55] Next, we improved the list of feasibility indicators based on input from key experts in the field, employed the framework to assess a different set of mitigation options, and assessed novel literature that appeared after SR1.5. Moreover, we developed novel ways to display the main findings that are easier to grasp, while still securing transparency and reproducibility of the assessment.

Overall, our feasibility assessment framework emphasizes that multiple factors would need to be considered and addressed to ensure rapid, upscaled, and sustained mitigation efforts. Importantly, the feasibility assessment does not aim to merely identify whether mitigation options are feasible. Rather, the assessment framework is aimed at identifying barriers to and enablers of the implementation of mitigation opportunities, to inform governments and decision makers what factors would need to be targeted to improve the feasibility of options to ensure that options can be implemented at scale on a timely basis. In doing so, we acknowledge that feasibility is not fixed, but that it is malleable and can change, either autonomously or as a result of targeted efforts of governments, industry, and other stakeholders (e.g., by implementing carbon pricing, subsidizing mitigation options, improving infrastructures for non-motorized transport, strengthening cross-sectoral coordination, or developing low carbon options). Table S1 shows that the barriers to and enablers of implementing mitigation options typically differ across contexts (including region), scales, and time, also illustrating that feasibility is malleable. As such, we introduce feasibility as a framework to understand the different factors that influence the deployment of individual mitigation options, which is critical to prioritize options and policy efforts. The assessment reveals which options can be readily implemented, as they face few implementation barriers. Moreover, the assessment highlights which changes and policies could increase the likelihood that mitigation options are implemented, as policies will be more effective if relevant barriers are reduced or removed and enablers of change brought into play. Based on the assessment, it can also be concluded that it would be better to refrain from implementing particular options (in some regions) altogether given the significant barriers they face.

The assessment also indicates where tailored approaches would be needed to enhance the feasibility of implementing relevant mitigation options by targeting context- and time-specific barriers and enablers (as identified in Table S1). To develop such tailored approaches, the feasibility assessment framework needs to be employed to identify barriers to and enablers of implementing specific mitigation options in specific regions or contexts. This may require additional research, as most indicators have probably not been assessed at a regional level. Such feasibility assessments can provide more detailed and concrete insights into which (national or local) policies could be implemented to enhance the feasibility of a given option in that specific context. Furthermore, feasibility assessments could be regularly repeated to understand to what extent the feasibility of options changes across time, which improves our understanding of how feasibility can be improved elsewhere as well.

Countries, governments, and decision makers in different roles may weigh the relative importance of the different feasibility dimensions and indicators differently, and prioritize their efforts accordingly. For example, some may find certain environmental, social, or health impacts more important than others, and some may consider impacts farther away, while others may be less likely to do so. Also, high financial costs may be a more prominent barrier in less-developed countries compared with highly developed countries. Similarly, options may be implemented and used despite their negative environmental or ecological externalities, in order to address other concerns. For example, in the current energy crisis, fossil fuel production is continued and even increased to secure access to energy, despite having many negative environmental impacts. This suggests that some options may still be implemented even though they face some barriers or externalities. Yet, other feasibility criteria may inhibit the implementation of a mitigation option in any region, such as the geophysical potential.

Our assessment focuses on the feasibility of specific mitigation options. Literature is emerging on the feasibility of mitigation pathways, which comprise multiple mitigation options.[3,107,108] The latter allows for the consideration of possible synergies and trade-offs between mitigation options, and immediate action versus delayed actions, acknowledging that the feasibility of options may change when different options are combined and when deployed at different times (e.g., now versus in a few decades). Moreover, it provides more comprehensive insight into the likelihood that mitigation pathways identified and assessed in integrated assessment models can be implemented and which system-level changes would be needed to remove barriers to the implementation of such mitigation pathways. Combining option- and system-level feasibility analyses has great added value. Specifically, the option-level analyses provide high granularity and detail, while the system-level analyses enable one to contextualize these analyses and to consider interactions and interdependencies between options.

For the purpose of the current paper, we did not conduct a systematic literature search to identify all relevant literature, but relied on systematic reviews whenever possible.[109] The feasibility framework introduced in this paper facilitates the integration of scattered insights of factors influencing the feasibility of deploying various mitigation options and the identification and prioritization of opportunities to enhance the potential of mitigation options. Also, our multidimensional framework helps to identify key research gaps that need to be addressed in the future, as it reveals which indicators have been understudied when assessing barriers to and enablers of deploying mitigation options. Clearly, interdisciplinary and transdisciplinary collaboration is pivotal to get a comprehensive view of the feasibility of different options, including scholars with expertise on specific feasibility dimensions (e.g., expertise on environmental, technical, economic, social, and institutional factors), sectoral experts (e.g., energy, land use, mobility), and experts on relevant regional differences. Additional efforts may be needed to train experts so as to ensure that the framework is employed consistently and to facilitate communication and collaboration between experts with different backgrounds so as to arrive at a comprehensive synthesis of the evidence base. Furthermore, a living open database could be set up to document and keep track of the relevant (emerging) evidence, which will facilitate future assessments as well as providing timely input for policy making.

The feasibility assessment approach identifies which factors inhibit and enable the implementation of mitigation options. An important next question is which factors affect the strength of the barriers and enablers. For example, Figure 1 reveals that public acceptance and uptake of electric vehicles is low in some jurisdictions. Follow-up studies can examine and review which factors increase public acceptance and adoption of electric vehicles to understand which factors would need to be targeted to remove this barrier.[110] Furthermore, future studies are needed to test which policies and changes would be effective to remove critical implementation barriers and to determine to what extent different enabling conditions, including strengthening multilevel governance, institutional capacity, policy instruments, technological innovation, transfer and mobilization of finance, and human behavior and lifestyle changes,[1] would enhance the feasibility of the deployment of mitigation options.

The feasibility assessment approach detailed above aims to address a critical question faced by many researchers and decision makers today: can we limit climate change, and if so, how? Our assessment reveals that, currently, many factors enable the implementation of mitigation options, but that significant policy efforts are needed to address different barriers so that the options can be deployed at scale. The results of such a feasibility assessment provide clear directions for climate policy, as they help in prioritizing efforts to mitigate climate change. Specifically, they reveal which options can be readily implemented because they face few barriers, which barriers would need to be removed, and which enablers could be strengthened to accelerate the deployment of mitigation options. Additional research may be needed to understand how different barriers can best be removed and how enablers can be put in place to enhance the feasibility of options. Importantly, the feasibility assessment approach is evidence based, involving a process that requires transparent and critical thinking about feasibility issues. As such, the feasibility assessment enables evidence-informed policy making, thereby preventing the risk that policy is based on inaccurate assumptions, misperceptions, and gut feelings.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2022.10.007.

AUTHOR CONTRIBUTIONS

L.S. and J.V. took a lead in developing the feasibility assessment approach and coordinated the assessment; all other authors provided input and feedback. H.d.C., K.d.K., and L.S. developed the feasibility assessment approach for mitigation options reported in SR1.5 of the IPCC, on which the feasibility assessment approach proposed in this paper is based. K.d.K., S.K., A.F.P.L., G.N., L.J.N., M.S., P.S., R.G., and H.M. assessed the feasibility of the options discussed in the paper and drafted the relevant text. M.T. assessed the level of deployment of the selected options in scenarios compliant with the Paris Agreement. L.S. took a lead in drafting the paper, and all authors provided feedback on the drafts.

DECLARATION OF INTERESTS

The authors declare no competing interests.

REFERENCES

1. IPCC (2018). Global warming of 1.5°C. In An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [V. Masson-Delmotte, P. Zhai, H.O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, and A. Pirani, et al., eds. (Cambridge University Press). https://doi.org/10.1017/9781009157940.
2. IPCC (2021). Summary for Policymakers. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, and S. Berger, et al., eds. (Cambridge University Press).
3. IPCC (2022). In Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, and R. Fradera, et al., eds. (Cambridge University Press). https://doi.org/10.1017/9781009157926.
4. IEA (2021). World Energy Outlook 2021 (Paris: IEA). https://iea.blob.core.windows.net/assets/ed3b983c-e2c9-401c-8633-749c3fefb375/WorldEnergyOutlook2021.pdf.
5. Amos, R. (2016). Bioenergy carbon capture and storage in global climate policy: examining the issues. Carbon & Climate Law Review *10*, 187–193. https://doi.org/10.2307/44134898.

6. Gamborg, C., Anker, H.T., and Sandøe, P. (2014). Ethical and legal challenges in bioenergy governance: coping with value disagreement and regulatory complexity. Energy Pol. *69*, 326–333. https://doi.org/10.1016/J.ENPOL.2014.02.013.

7. Naiki, Y. (2016). Trade and bioenergy: explaining and assessing the regime complex for sustainable bioenergy. Eur. J. Int. Law *27*, 129–159. https://doi.org/10.1093/ejil/chw004.

8. Torvanger, A. (2019). Governance of bioenergy with carbon capture and storage (BECCS): accounting, rewarding, and the Paris agreement. Clim. Pol. *19*, 329–341. https://doi.org/10.1080/14693062.2018.1509044.

9. Gerten, D., Heck, V., Jägermeyr, J., Bodirsky, B.L., Fetzer, I., Jalava, M., Kummu, M., Lucht, W., Rockström, J., Schaphoff, S., and Schellnhuber, H.J. (2020). Feeding ten billion people is possible within four terrestrial planetary boundaries. Nat. Sustain. *3*, 200–208. https://doi.org/10.1038/s41893-019-0465-1.

10. Heck, V., Gerten, D., Lucht, W., and Popp, A. (2018). Biomass-based negative emissions difficult to reconcile with planetary boundaries. Nat. Clim. Chang. *8*, 151–155. https://doi.org/10.1038/s41558-017-0064-y.

11. IPCC (2020). In Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems, P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, and R. van Diemen, et al., eds., In press.

12. Schyns, J.F., Hoekstra, A.Y., Booij, M.J., Hogeboom, R.J., and Mekonnen, M.M. (2019). Limits to the world's green water resources for food, feed, fiber, timber, and bioenergy. Proc. Natl. Acad. Sci. USA. *116*, 4893–4898. https://doi.org/10.1073/pnas.1817380116.

13. Kenworthy, J., and Schiller, P.L. (2018). An Introduction to Sustainable Transportation: Policy, Planning and Implementation (Routledge).

14. Newman, P., Beatley, T., and Boyer, H. (2017). Resilient Cities: Overcoming Fossil Fuel Dependence (Island Press).

15. Balcombe, P., Brierley, J., Lewis, C., Skatvedt, L., Speirs, J., Hawkes, A., and Staffell, I. (2019). How to decarbonise international shipping: options for fuels, technologies and policies. Energy Convers. Manag. *182*, 72–88. https://doi.org/10.1016/j.enconman.2018.12.080.

16. Müller-Casseres, E., Carvalho, F., Nogueira, T., Fonte, C., Império, M., Poggio, M., Wei, H.K., Portugal-Pereira, J., Rochedo, P.R., Szklo, A., and Schaeffer, R. (2021). Production of alternative marine fuels in Brazil: an integrated assessment perspective. Energy *219*, 119444. https://doi.org/10.1016/j.energy.2020.119444.

17. Sharmina, M., Edelenbosch, O.Y., Wilson, C., Freeman, R., Gernaat, D.E.H.J., Gilbert, P., Larkin, A., Littleton, E.W., Traut, M., Van Vuuren, D.P., et al. (2021). Decarbonisation the critical sectors of aviation, shipping, road freight and industry to limit warming to 1.5-2°C. Clim. Pol. *21*, 455–474. https://doi.org/10.1080/14693062.2020.1831430.

18. Bataille, C., Åhman, M., Neuhoff, K., Nilsson, L.J., Fischedick, M., Lechtenböhmer, S., Solano-Rodriquez, B., Denis-Ryan, A., Stiebert, S., Waisman, H., et al. (2018). A review of technology and policy deep decarbonization pathway options for making energy intensive industry production consistent with the Paris Agreement. J. Clean. Prod. *187*, 960–973. https://doi.org/10.1016/j.jclepro.2018.03.107.

19. Nilsson, L.J., Bauer, F., Åhman, M., Andersson, F.N.G., Bataille, C., de la Rue du Can, S., Ericsson, K., Hansen, T., Johansson, B., Lechtenböhmer, S., et al. (2021). An industrial policy framework for transforming energy and emissions intensive industries towards zero emissions. Clim. Pol. *21*, 1053–1065. https://doi.org/10.1080/14693062.2021.1957665.

20. Vogl, V., Åhman, M., and Nilsson, L.J. (2021). The making of green steel in the EU: a policy evaluation for the early commercialization phase. Clim. Pol. *21*, 78–92. https://doi.org/10.1080/14693062.2020.1803040.

21. Costa, I., Rochedo, P., Costa, D., Ferreira, P., Araújo, M., Schaeffer, R., and Szklo, A. (2019). Placing hubs in CO2 pipelines: an application to industrial CO2 emissions in the Iberian Peninsula. Appl. Energy *236*, 22–31. https://doi.org/10.1016/j.apenergy.2018.11.050.

22. Middleton, R.S., and Yaw, S. (2018). The cost of getting CCS wrong: Uncertainty, infrastructure design, and stranded CO2. Int. J. Greenh. Gas Control *70*, 1–11. https://doi.org/10.1016/j.ijggc.2017.12.011.

23. Allen, P., and Chatterton, T. (2013). Carbon reduction scenarios for 2050: an explorative analysis of public preferences. Energy Pol. *63*, 796–808. https://doi.org/10.1016/j.enpol.2013.08.079.

24. Demski, C., Spence, A., and Pidgeon, N. (2017). Effects of exemplar scenarios on public preferences for energy futures using the my2050 scenario-building tool. Nat. Energy *2*, 1–7. https://doi.org/10.1038/nenergy.2017.27.

25. L'Orange Seigo, S., Dohle, S., and Siegrist, M. (2014). Public perception of carbon capture and storage (CCS): a review. Renew. Sustain. Energy Rev. *38*, 848–863. https://doi.org/10.1016/j.rser.2014.07.017.

26. Terwel, B.,W., Ter Mors, E., and Daamen, D.D. (2012). It's not only about safety: beliefs and attitudes of 811 local residents regarding a CCS project in Barendrecht. Int. J. Greenh. Gas Control *9*, 41–51. https://doi.org/10.1016/j.ijggc.2012.02.017.

27. Cox, E., Spence, E., and Pidgeon, N. (2020). Public perceptions of carbon dioxide removal in the United States and the United Kingdom. Nat. Clim. Chang. *10*, 744–749. https://doi.org/10.1038/s41558-020-0823-z.

28. Smith, P., Freidmann, J., Fuss, S., Deich, N., Amador, G., Minx, J., Lawrence, M., Bustamante, M., Masera, O., Cowie, A., et al. (2017). Bridging the gap - carbon dioxide removal. In In: UNEP, The UNEP Emissions Gap Report, pp. 58–66. (UNEP).

29. Zeiske, N. (2021). The Intrinsic Route to Pro-environmental Behaviour (Faculty of Behavioural and Social Sciences, University of Groningen). PhD Thesis.

30. Collier, E.S., Oberrauter, L.-M., Normann, A., Norman, C., Svensson, M., Niimi, J., and Bergman, P. (2021). Identifying barriers to decreasing meat consumption and increasing acceptance of meat substitutes among Swedish consumers. Appetite *167*, 105643. https://doi.org/10.1016/j.appet.2021.105643.

31. Milfont, T.L., Satherley, N., Osborne, D., Wilson, M.S., and Sibley, C.G. (2021). To meat, or not to meat: a longitudinal investigation of transitioning to and from plant-based diets. Appetite *166*, 105584. https://doi.org/10.1016/j.appet.2021.105584.

32. Hoek, A.C., Luning, P.A., Weijzen, P., Engels, W., Kok, F.J., and De Graaf, C. (2011). Replacement of meat by meat substitutes. A survey on person- and product-related factors in consumer acceptance. Appetite *56*, 662–673. https://doi.org/10.1016/j.appet.2011.02.001.

33. Michel, F., Hartmann, C., and Siegrist, M. (2021). Consumers' associations, perceptions and acceptance of meat and plant-based meat alternatives. Food Qual. Prefer. *87*, 104063. https://doi.org/10.1016/j.foodqual.2020.104063.

34. FAO (2020). Meat Food Supply Quantity. http://www.fao.org/faostat/en/?#data/. (Accessed 31 August 2021).

35. Portugal-Pereira, J., Ferreira, P., Cunha, J., Szklo, A., Schaeffer, R., and Araújo, M. (2018). Better late than never, but never late is better: risk assessment of nuclear power construction projects. Energy Pol. *120*, 158–166. https://doi.org/10.1016/j.enpol.2018.05.041.

36. Corner, A., Venables, D., Spence, A., Poortinga, W., Demski, C., and Pidgeon, N. (2011). Nuclear power, climate change and energy security: exploring British public attitudes. Energy Pol. *39*, 4823–4833. https://doi.org/10.1016/j.enpol.2011.06.037.

37. Hobman, E.V., and Ashworth, P. (2013). Public support for energy sources and related technologies: the impact of simple information provision. Energy Pol. *63*, 862–869. https://doi.org/10.1016/j.enpol.2013.09.011.

38. Pampel, F.C. (2011). Support for Nuclear Energy in the Context of Climate Change: Evidence from the European Union*24* (Organization & Environment), pp. 249–268. https://doi.org/10.1177/1086026611422261.

39. Bruckner, T., et al. (2014). Energy systems. In Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, and P. Eickemeier, et al., eds. (Cambridge University Press).

40. Aung, T.W., Jain, G., Sethuraman, K., Baumgartner, J., Reynolds, C., Grieshop, A.P., Marshall, J.D., and Brauer, M. (2016). Health and climate-relevant pollutant concentrations from a carbon-finance approved cookstove intervention in rural India. Environ. Sci. Technol. *50*, 7228–7238. https://doi.org/10.1021/acs.est.5b06208.

41. Hanna, R., Duflo, E., and Greenstone, M. (2016). Up in smoke: the influence of household behavior on the long-run impact of improved cooking stoves. Am. Econ. J. Econ. Pol. *8*, 80–114. https://doi.org/10.1257/pol.20140008.

42. Patange, O.S., Ramanathan, N., Rehman, I.H., Tripathi, S.N., Misra, A., Kar, A., Graham, E., Singh, L., Bahadur, R., and Ramanathan, V. (2015). Reductions in indoor black carbon concentrations from improved biomass stoves in rural India. Environ. Sci. Technol. *49*, 4749–4756. https://doi.org/10.1021/es506208x.

43. Wathore, R., Mortimer, K., and Grieshop, A.P. (2017). In-use emissions and estimated impacts of traditional, natural- and forced-draft cookstoves in rural Malawi. Environ. Sci. Technol. *51*, 1929–1938. https://doi.org/10.1021/acs.est.6b05557.

44. Maibach, E., Steg, L., and Anable, J. (2009). Promoting physical activity and reducing climate change: opportunities to replace short car trips with

active transportation. Prev. Med. *49*, 326–327. https://doi.org/10.1016/j.ypmed.2009.06.028.

45. IRENA (2020). Renewable Energy and Jobs: Annual Review 2020 (International Renewable Energy Agency).
46. Mahmud, M., Huda, N., Farjana, S., and Lang, C. (2018). Environmental impacts of solar-photovoltaic and solar-thermal systems with life-cycle assessment. Energies *11*, 2346. https://doi.org/10.3390/en11092346.
47. IRENA (2020). Renewable Power Generation Costs in 2019 (International Renewable Energy Agency).
48. Miranda, R.F., Szklo, A., and Schaeffer, R. (2015). Technical-economic potential of PV systems on Brazilian rooftops. Renew. Energy *75*, 694–713. https://doi.org/10.1016/j.renene.2014.10.037.
49. Dinesh, H., and Pearce, J.M. (2016). The potential of agrivoltaic systems. Renew. Sustain. Energy Rev. *54*, 299–308. https://doi.org/10.1016/j.rser.2015.10.024.
50. Abreu, E.F., Canhoto, P., Prior, V., and Melicio, R. (2018). Solar resource assessment through long-term statistical analysis and typical data generation with different time resolutions using GHI measurements. Renew. Energy *127*, 398–411. https://doi.org/10.1016/j.renene.2018.04.068.
51. Diagne, M., David, M., Lauret, P., Boland, J., and Schmutz, N. (2013). Review of solar irradiance forecasting methods and a proposition for small-scale insular grids. Renew. Sustain. Energy Rev. *27*, 65–76. https://doi.org/10.1016/j.rser.2013.06.042.
52. Bessette, D.L., and Arvai, J.L. (2018). Engaging attribute tradeoffs in clean energy portfolio development. Energy Pol. *115*, 221–229. https://doi.org/10.1016/j.enpol.2018.01.021.
53. Hanger, S., Komendantova, N., Schinke, B., Zejli, D., Ihlal, A., and Patt, A. (2016). Community acceptance of large-scale solar energy installations in developing countries: evidence from Morocco. Energy Res. Soc. Sci. *14*, 80–89. https://doi.org/10.1016/j.erss.2016.01.010.
54. Hazboun, S.O., and Boudet, H.S. (2020). Public preferences in a shifting energy future: comparing public views of eight energy sources in North America's Pacific Northwest. Energies *13*, 1940–2021. https://doi.org/10.3390/en13081940.
55. Jobin, M., and Siegrist, M. (2018). We choose what we like - affect as a driver of electricity portfolio choice. Energy Pol. *122*, 736–747. https://doi.org/10.1016/j.enpol.2018.08.027.
56. Ma, C., Rogers, A.A., Kragt, M.E., Zhang, F., Polyakov, M., Gibson, F., Chalak, M., Pandit, R., and Tapsuwan, S. (2015). Consumers' willingness to pay for renewable energy: a meta-regression analysis. Resour. Energy Econ. *42*, 93–109. https://doi.org/10.1016/j.reseneeco.2015.07.003.
57. IEA (2019). Material Efficiency in Clean Energy Transitions (IEA)). https://doi.org/10.1787/aeaaccd8-en.
58. Bellamy, R., and Geden, O. (2019). Govern CO2 removal from the ground up. Nat. Geosci. *12*, 874–876. https://doi.org/10.1038/s41561-019-0475-7.
59. Balaban, O., and Puppim de Oliveira, J.A. (2017). Sustainable buildings for healthier cities: assessing the co-benefits of green buildings in Japan. J. Clean. Prod. *163*, S68–S78. https://doi.org/10.1016/j.jclepro.2016.01.086.
60. Curl, A., Kearns, A., Mason, P., Egan, M., Tannahill, C., and Ellaway, A. (2015). Physical and mental health outcomes following housing improvements: evidence from the GoWell study. J. Epidemiol. Community Health *69*, 12–19. https://doi.org/10.1136/jech-2014-204064.
61. Karlsson, M., Alfredsson, E., and Westling, N. (2020). Climate policy co-benefits: a review. Clim. Pol. *20*, 292–316. https://doi.org/10.1080/14693062.2020.1724070.
62. Lacroix, E., and Chaton, C. (2015). Fuel poverty as a major determinant of perceived health: the case of France. Publ. Health *129*, 517–524. https://doi.org/10.1016/j.puhe.2015.02.007.
63. Levy, J.I., Woo, M.K., Penn, S.L., Omary, M., Tambouret, Y., Kim, C.S., and Arunachalam, S. (2016). Carbon reductions and health co-benefits from US residential energy efficiency measures. Environ. Res. Lett. *11*, 034017. https://doi.org/10.1088/1748-9326/11/3/034017.
64. Liddell, C., and Guiney, C. (2015). Living in a cold and damp home: frameworks for understanding impacts on mental well-being. Publ. Health *129*, 191–199. https://doi.org/10.1016/j.puhe.2014.11.007.
65. MacNaughton, P., Cao, X., Buonocore, J., Cedeno-Laurent, J., Spengler, J., Bernstein, A., and Allen, J. (2018). Energy savings, emission reductions, and health co-benefits of the green building movement review-article. J. Expo. Sci. Environ. Epidemiol. *28*, 307–318. https://doi.org/10.1038/s41370-017-0014-9.
66. Ortiz, J., Casquero-Modrego, N., and Salom, J. (2019). Health and related economic effects of residential energy retrofitting in Spain. Energy Pol. *130*, 375–388. https://doi.org/10.1016/j.enpol.2019.04.013.
67. Payne, J., Downy, F., and Weatherall, D. (2015). Capturing the ''multiple benefits'' of energy efficiency in practice: the UK example. ECEEE 2015 Summer Study, 229–238.
68. Poortinga, W., Jiang, S., Grey, C., and Tweed, C. (2018). Impacts of energy-efficiency investments on internal conditions in low-income households. Build. Res. Inf. *46*, 653–667. https://doi.org/10.1080/09613218.2017.1314641.
69. Smith, A.C., Holland, M., Korkeala, O., Warmington, J., Forster, D., ApSimon, H., Oxley, T., Dickens, R., and Smith, S.M. (2016). Health and environmental co-benefits and conflicts of actions to meet UK carbon targets. Clim. Pol. *16*, 253–283. https://doi.org/10.1080/14693062.2014.980212.
70. Thomson, H., and Thomas, S. (2015). Developing empirically supported theories of change for housing investment and health. Soc. Sci. Med. *124*, 205–214. https://doi.org/10.1016/j.socscimed.2014.11.043.
71. Tonn, B., Rose, E., and Hawkins, B. (2018). Evaluation of the U.S. department of energy's weatherization assistance program: impact results. Energy Pol. *118*, 279–290. https://doi.org/10.1016/j.enpol.2018.03.051.
72. Willand, N., Ridley, I., and Maller, C. (2015). Towards explaining the health impacts of residential energy efficiency interventions - a realist review. Part 1: Pathways. Soc. Sci. Med. *133*, 191–201. https://doi.org/10.1016/j.socscimed.2015.02.005.
73. Drews, S., and van den Bergh, J.C. (2016). What explains public support for climate policies? A review of empirical and experimental studies. Clim. Pol. *16*, 855–876. https://doi.org/10.1080/14693062.2015.1058240.
74. Perlaviciute, G., and Steg, L. (2014). Contextual and psychological factors shaping evaluations and acceptability of energy alternatives: integrated review and research agenda. Renew. Sustain. Energy Rev. *35*, 361–381. https://doi.org/10.1016/j.rser.2014.04.003.
75. Schuitema, G., Steg, L., and Rothengatter, J.A. (2010). Relationship between the acceptability, personal outcome expectations and the expected effects of transport pricing policies. J. Environ. Psychol. *30*, 587–593. https://doi.org/10.1016/j.jenvp.2010.05.002.
76. Jewell, J., and Cherp, A. (2019). On the political feasibility of climate change mitigation pathways: is it too late to keep warming below 1.5°C? WIREs Clim. Change *11*, e621. https://doi.org/10.1002/wcc.621.
77. Schuitema, G., Steg, L., and Van Kruining, M. (2011). When are transport policies fair and acceptable? The role of six fairness principles. Soc. Justice Res. *24*, 66–84. https://doi.org/10.1007/s11211-011-0124-9.
78. Gurney, K.R., Kılkış, Ş., Seto, K.C., Lwasa, S., Moran, D., Riahi, K., Keller, M., Rayner, P., and Luqman, M. (2022). Greenhouse gas emissions from global cities under SSP/RCP scenarios, 1990 to 2100. Global Environ. Change *73*, 102478. https://doi.org/10.1016/j.gloenvcha.2022.102478.
79. Cedeño-Laurent, J.G., Williams, A., Macnaughton, P., Cao, X., Eitland, E., Spengler, J., and Allen, J. (2018). Building evidence for health: green buildings, current science, and future challenges. Annu. Rev. Public Health *39*, 291–308. https://doi.org/10.1146/annurev-publhealth-031816-044420.
80. Fisk, W.J. (2018). How home ventilation rates affect health: a literature review. Indoor Air *28*, 473–487. https://doi.org/10.1111/ina.12469.
81. Hamilton, I., Milner, J., Chalabi, Z., Das, P., Jones, B., Shrubsole, C., Davies, M., and Wilkinson, P. (2015). Health effects of home energy efficiency interventions in England: a modelling study. BMJ Open *5*, 0072988–e7311. https://doi.org/10.1136/bmjopen-2014-007298.
82. Militello-Hourigan, R.E., and Miller, S.L. (2018). The impacts of cooking and an assessment of indoor air quality in Colorado passive and tightly constructed homes. Build. Environ. *144*, 573–582. https://doi.org/10.1016/j.buildenv.2018.08.044.
83. Underhill, L.J., Fabian, M.P., Vermeer, K., Sandel, M., Adamkiewicz, G., Leibler, J.H., and Levy, J.I. (2018). Modeling the resiliency of energy-efficient retrofits in low-income multifamily housing. Indoor Air *28*, 459–468. https://doi.org/10.1111/ina.12446.
84. Nilsson, M., Griggs, D., and Visbeck, M. (2016). Policy: map the interactions between sustainable development goals. Nature *534*, 320–322. https://doi.org/10.1038/534320a.
85. Göswein, V., Reichmann, J., Habert, G., and Pittau, F. (2021). Land availability in Europe for a radical shift toward bio-based construction. Sustain. Cities Soc. *70*, 102929. https://doi.org/10.1016/j.scs.2021.102929.
86. Pomponi, F., Hart, J., Arehart, J.H., and D'Amico, B. (2020). Buildings as global carbon sinks? A reality check on feasibility limits. One Earth *3*, 157–161. https://doi.org/10.1016/j.oneear.2020.07.018.
87. Gielen, D., Saygin, D., Taibi, E., and Birat, J. (2020). Renewables-based decarbonization and relocation of iron and steel making: a case study. J. Ind. Ecol. *24*, 1113–1125. https://doi.org/10.1111/jiec.12997.

88. Bataille, C., Nilsson, L., and Jotzo, F. (2021). Industry in a net-zero emissions world - uprooting of supply chains, broader policy thinking, and how to model it all. Energy Strategy Rev., in press.
89. Comello, S.D., Reichelstein, S.J., Sahoo, A., and Schmidt, T.S. (2017). Enabling mini-grid development in rural India. World Dev. *93*, 94–107. https://doi.org/10.1016/j.worlddev.2016.12.029.
90. Shukla, A.K., Sudhakar, K., Baredar, P., and Mamat, R. (2018). Solar PV and BIPV system: barrier, challenges and policy recommendation in India. Renew. Sustain. Energy Rev. *82*, 3314–3322. https://doi.org/10.1016/j.rser.2017.10.013.
91. Kampker, A., Ayvaz, P., Schön, C., Karstedt, J., Förstmann, R., and Welker, F. (2020). Challenges towards large-scale fuel cell production: results of an expert assessment study. Int. J. Hydrogen Energy *45*, 29288–29296. https://doi.org/10.1016/j.ijhydene.2020.07.180.
92. Pollet, B.G., Kocha, S.S., and Staffell, I. (2019). Current status of automotive fuel cells for Sustainable transport. Current Opinion in Electrochemistry *16*, 90–95. https://doi.org/10.1016/j.coelec.2019.04.021.
93. Wang, J., Wang, H., and Fan, Y. (2018). Techno-economic challenges of fuel cell commercialization. Engineering *4*, 352–360. https://doi.org/10.1016/j.eng.2018.05.007.
94. Brown, M.A., Soni, A., Lapsa, M.V., Southworth, K., and Cox, M. (2020). High energy burden and low-income energy affordability: conclusions from a literature review. Prog. Energy *2*, 042003. https://doi.org/10.1088/2516-1083/abb954.
95. Canepa, K., Hardman, S., and Tal, G. (2019). An early look at plug-in electric vehicle adoption in disadvantaged communities in California. Transport Pol. *78*, 19–30. https://doi.org/10.1016/j.tranpol.2019.03.009.
96. Madeddu, S., Ueckerdt, F., Pehl, M., Peterseim, J., Lord, M., Kumar, K.A., Krüger, C., and Luderer, G. (2020). The CO2 reduction potential for the European industry via direct electrification of heat supply (power-to-heat). Environ. Res. Lett. *15*, 124004. https://doi.org/10.1088/1748-9326/abbd02.
97. Bauer, F., Hansen, T., and Nilsson, L.J. (2022). Assessing the feasibility of archetypal transition pathways towards carbon neutrality - a comparative analysis of European industries. Resour. Conserv. Recycl. *177*, 106015. https://doi.org/10.1016/j.resconrec.2021.106015.
98. Bataille, C., Nilsson, L.J., and Jotzo, F. (2021). Industry in a net-zero emissions world: new mitigation pathways, new supply chains, modelling needs and policy implications. Energy and Climate Change *2*, 100059. https://doi.org/10.1016/j.egycc.2021.100059.
99. Bataille, C., Stiebert, S., and Li, F.G.N. (2021). Global facility level net-zero steel pathways, technical report on the first scenarios of the Net-zero Steel Projet, IDDRI. Available online: http://netzerosteel.org
100. Meys, R., Kätelhön, A., Bachmann, M., Winter, B., Zibunas, C., Suh, S., and Bardow, A. (2021). Achieving net-zero greenhouse gas emission plastics by a circular carbon economy. Science *374*, 71–76. https://doi.org/10.1126/science.abg9853.
101. Bauer, F., and Fontenit, G. (2021). Plastic dinosaurs - digging deep into the accelerating carbon lock-in of plastics. Energy Pol. *156*, 112418. https://doi.org/10.1016/j.enpol.2021.112418.
102. Mah, A. (2021). Future-proofing capitalism: the paradox of the circular economy for plastics. Glob. Environ. Polit. *21*, 121–142. https://doi.org/10.1162/glep_a_00594.
103. Nielsen, K.S., Stern, P.C., Dietz, T., Gilligan, J.M., Van Vuuren, D.P., Figueroa, M.J., Folke, C., Gwozdz, W., Ivanova, D., Reisch, L.A., et al. (2020). Improving climate change mitigation analysis: a framework for assessing feasibility. One Earth *3*, 325–336. https://doi.org/10.1016/j.oneear.2020.08.007.
104. Deng, H.-M., Liang, Q.-M., Liu, L.-J., and Anadon, L.D. (2018). Co-benefits of greenhouse gas mitigation: a review and classification by type, mitigation sector, and geography. Environ. Res. Lett. *12*, 123001. https://doi.org/10.1088/1748-9326/aa98d2.
105. Harrison, M.T., Cullen, B.R., Mayberry, D.E., Cowie, A.L., Bilotto, F., Badgery, W.B., Liu, K., Davison, T., Christie, K.M., Muleke, A., and Eckard, R.J. (2021). Carbon myopia: the urgent need for integrated social, economic, and environmental action in the livestock sector. Glob. Chang. Biol. *27*, 5726–5761. https://doi.org/10.1111/gcb.15816.
106. Singh, C., Bazaz, A., Ley, D., Ford, J., and Revi, A. (2020). Assessing the feasibility of climate change adaptation options in the water sector: examples from rural and urban landscapes. Water Security *11*, 100071. https://doi.org/10.1016/j.wasec.2020.100071.
107. Brutschin, E., Pianta, S., Tavoni, M., Riahi, K., Bosetti, V., Marangoni, G., and van Ruijven, B.J. (2021). The mulidimensional feasibilty evaluation of low-cabon scenarios. Environ. Res. Lett. *16*, 064069. https://doi.org/10.1088/1748-9326/abf0ce.
108. Warszawski, L., Kriegler, E., Lenton, T.M., Gaffney, O., Jacob, D., Klingenfeld, D., Koide, R., Costa, M.M., Messner, D., Nakicenovic, N., et al. (2021). All options, no silver bullets, needed to limit global warming to 1.5°C: a scenario appraisal. Environ. Res. Lett. *16*, 064037. https://doi.org/10.1088/1748-9326/abfeec.
109. Lamb, W.F., Creutzig, F., Callaghan, M.W., and Minx, J.C. (2019). Learning about urban climate solutions from case studies. Nat. Clim. Chang. *9*, 279–287. https://doi.org/10.1038/s41558-019-0440-x.
110. Steg, L., and Vlek, C. (2009). Encouraging pro-environmental behaviour: an integrative review and research agenda. J. Environ. Psychol. *29*, 309–317. https://doi.org/10.1016/j.jenvp.2008.10.004.