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

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Abstract:	This paper aims to present a comprehensive framework to assess which factors inhibit and enable the implementation of mitigation options to reach global climate goals. We propose that six dimensions are critical to understand the feasibility of implementing mitigation options: geophysical, environmental-ecological, technological, economic, socio-cultural and institutional feasibility, and identify key criteria for each dimension that are critical for assessing the feasibility of mitigation options. We demonstrate the approach by assessing to what extent each criterion and dimension enables or inhibits

	the implementation of some specific mitigation options in different sectors. The assessment reveals what would be the key barriers to implement different options, and what factors would need to be addressed to remove these barriers as to increase the feasibility of options. As such, the feasibility framework addresses a critical question of policy makers: can we limit global climate change, and how can we do this?
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A method to identify barriers and enablers of implementing climate change mitigation options

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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, socio-cultural 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 few barriers would need to be addressed to implement solar energy at scale.

Keywords: feasibility; mitigation options; barriers; enablers; geophysical; environmental-ecological; technological; economic; socio-cultural; institutional

Highlights

- We present a framework to assess the feasibility of mitigation options.
- Six dimensions are critical for the feasibility of mitigation options.
- Feasibility of mitigation options varies across context, time and scale.
- Institutional factors inhibit the implementation of many mitigation options.

In brief

Mitigation options are not implemented at the scale required to limit global warming to well below 2°C. An integrated assessment of key factors that inhibit and enable the implementation of mitigation options is currently lacking, but critical to prioritising options and policies to promote their employment. Here we present a comprehensive framework to assess which factors inhibit and enable the implementation of mitigation options. The framework identifies six dimensions that are critical for the feasibility of mitigation options: geophysical, environmental-ecological, technological, economic, socio-cultural and institutional feasibility.

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 to 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 to limit global warming to well below 2°C, and preferably to 1.5°C, compared to 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 motorised transport, home energy savings), dietary changes (i.e., less animal proteins), 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 PV, 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.[2,3,4] It is therefore critical to understand which factors affect the likelihood that promising mitigation options are 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[5,6,7,8,] 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.[15,16,17] International competition is a challenge for decarbonising the production of emissions-intensive basic materials, since such production typically entails higher production costs.[18,19,20] Carbon capture and storage is logistically challenging[21,22], and is generally not supported by the public.[23,24,25,26] 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], to reduce meat consumption[30,31], and have negative attitudes towards 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 generating capacity is significantly costly, associated with high investment risks, and regulatory, political and management contingences cause delays in reactor construction.[35] Nuclear power also faces public resistance[36,37,38], and causes intergenerational inequity.[39] Improved biomass burning cook-stoves 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, fail to maintain them, and their usage declines over time.[40,41,42,43] 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 realisation of their full mitigation potential. For example, a shift to non-motorised transport would not only limit climate change, but is also 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 PV is an economically viable option[47,48], is not likely to compete strongly with food production[49], has a high technical potential[48,50,51], and is generally widely supported by the public.[52,53,54,55,56] 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 wellbeing by alleviating fuel poverty, reducing fuel consumption and associated financial stress, and improving ambient air quality.[59,60,61,62,63,64,65,66,67,68,69,70,71,72] Yet, such enabling factors, even when identified and available, are not always utilised to support mitigation efforts, representing an underutilised 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 favourable environmental outcomes, even when such options are associated with some costs.[73,74,75]

In sum, a wide range of factors has been identified that affects 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 implement 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 to their implementation.

In this paper, we aim to introduce a comprehensive framework to understand 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 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. Particularly institutional factors inhibit the implementation of many options that need to be 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 timely at scale.

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, socio-cultural 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, socio-cultural factors, or institutional factors), and detailed knowledge on 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 implement an option (e.g., availability of water flows 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 absolutely feasible or not), 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 economic effects of mitigation options. Two indicators reflect the economic feasibility: how costly it is to implement the option, both in the short and 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.

Socio-cultural 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 socio-cultural feasibility. First, an option is more feasible when the public supports the option and is willing to change their behaviour accordingly (e.g., by adopting and using the relevant option). Second, socio-cultural feasibility is enhanced when an option has positive (rather than negative) impacts on human health and wellbeing. Third, options are more feasible and acceptable if they enhance equity and justice 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 multi-dimensional 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, change in building construction, carbon capture and storage) as well as demand side options (e.g. changes in diets, reductions in motorised 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 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 only included in 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 is assessed whether an indicator would generally have a positive, negative, or both have 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.[60,62,64,68,70,72,79,80,81,82,83] In sum, the following scores are used in the assessment [cf. 84] to systematise the multi-dimensional assessment:

- \- the indicator poses a barrier to implementing the option, e.g., it is associated with high costs, pollution, land use, or low public or political acceptance.
- ± 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 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 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 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), which 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, signalling 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 scale 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.[91,92,93] Therefore, Table 2 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 2, which indicates whether the effect of the indicator on feasibility of the options differs across context, time and scale. Table 2 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 2 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 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 socio-cultural and institutional barriers in many countries. Specifically, solar energy is generally supported by the public, and has positive impacts on human health and wellbeing. Yet, high upfront costs may deter adaption of solar PV 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 decarbonisation 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%-+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 scale 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 wellbeing. In addition, this option faces some technological barriers, as some solutions are still rather under development and 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 ten (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 by 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 the energy and emissions intensive industry is more challenging.[18,96] The complexity and heterogeneity of heavy industry means that the role and maturity of electrification options vary across sub-sectors, 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/). 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 TWh's, the electrification of primary plastics production may require 10 000 TWh (~40 % of current global demand) or more, indicating the different scales involved that has implications for their feasibility.[99,100] Also, the plastics and petrochemical sectors do not yet seem to consider decarbonisation as a feasible prospect in light of their heavy investments into 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 in general. Table 2 shows that the enablers and barriers of the implementation of most of the options vary across regions, scale and time. Importantly, most options face barriers when they are implemented at a large scale, though 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 2 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). In order 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 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 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 to mitigate 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[76], 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 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.

Further, 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 in the first place, and at what scale, 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 for 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 PV.[47,54,55] Next, we improved the list of feasibility indicators based on input from key experts in the field, employ the framework to assess a different set of mitigation options, and assess novel literature that appeared since 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 emphasises 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 or not mitigation options are feasible. Rather, the assessment framework is aimed at identifying barriers 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 timely at scale. 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, subsidising mitigation options, improving infrastructures for non-motorised transport, strengthening cross-sectoral coordination, or developing low carbon options). Table 2 shows that the barriers and enablers to implement mitigation options typically differs across context (including region), scale 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 prioritise 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 be also 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 2). To develop such tailored approaches, the feasibility assessment framework needs to be employed to identify barriers 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 prioritise their efforts accordingly. For example, some may find certain environmental, social or health impact more important than others, and some may consider impacts further 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 to high 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 of 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 for 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 enables to contextualise 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 varied mitigation options, and to identify and prioritise opportunities to enhance the potential of mitigation options. Also, our multi-dimensional framework helps to identify key research gaps that need to be addressed in future research, as it reveals which indicators have been understudied when assessing barriers 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 as to ensure that the framework is employed consistently, and to facilitate communication and collaboration between experts with different backgrounds 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 provide timely input for policy making.

The feasibility assessment approach identifies which factors inhibit and enable the implementation of mitigation options. An important net 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 mobilisation of finance, and human behaviour 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. Results of such a feasibility assessment provide clear directions for climate policy, as it helps in prioritising efforts to mitigate climate change. Specifically, it reveals which options can be readily implemented since they face few barriers, and 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.

Author contributions

LS and JV took a lead in developing the feasibility assessment approach, and coordinated the assessment; all other authors provided input and feedback. HdC, KdK, and LS 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. KdK, SK, AFPL, GN, LJN, MS, PS, RG and HM assessed the feasibility of the options discussed in the paper, and drafted the relevant text. MT assessed the level of deployment of the selected options in scenarios compliant with the Paris Agreement. LS took a lead in drafting the paper, all authors provided feedback on the drafts.

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Figure captions

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

Note Figure 1. Blue bars indicate the extent to which the indicator enables the implementation of the option (E) 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 whether the indicator affects the feasibility of the option. The shading indicates the level of confidence, with darker shading signifying higher levels of confidence.

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

Note Figure 2: Blue bars indicate the extent of enablers to 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)

Table 1. Dimensions and indicators to assess the barriers 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	· Simplicity: is the option technically simple to operate, maintain, and integrate

technology can be implemented at scale quickly	· 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
Socio-cultural feasibility: public engagement and support, and health, wellbeing and distributional effects	· Public acceptance: the extent to which the public supports the option and will change their behaviour accordingly · Effects on health and wellbeing (excluding environmental-ecological impacts) · Distributional effects: equity and justice across groups, regions and generations, including security of energy, water, food and poverty
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

Table 2. Line of sight of the assessment of the feasibility of the options presented in Figure 1, and an overview of the extent to which the feasibility of the options may differ across context (e.g., region), time (e.g., 2030 versus 2050), and scale (e.g., small versus large).

	Geophysical					
	Physical potential		**Geophysical recourses**		**Land use**	
	Line of sight	**Role of context**	**Line of sight**	**Role of context**	**Line of sight**	**Role of context**
Solar energy	1	Limited in higher latitudes	2	Not limited by materials	3	Limited in urban areas
Integrating sectors, strategies and innovations	4,5	Ability to reduce pressures on physical land resources for urban areas	6–14	Depends on lowering the material demands for urban development with opportunities for considering materials with lower GHG impacts and selection of urban development plans with lower material demands	5,15,16	Increases with the role of urban land use and spatial planning in low carbon development and the relevance of brownfield urban development for the project
Envelope improvement	17–35	- Not applicable in historical/heritage buildings where modifications to facade are difficult - Transparent insulation materials provide the advantages of insulation materials including also the advantages of being able to use daylight	17–35	- Conventional insulation materials are derived from petrochemical substance, but new sustainable insulation materials have been developed - Environmental impacts of green roofs depends on the selection of efficient and sustainable components. Green walls	17–35	NA

		- Green Roofs enhance building aesthetics and reduce heat gains and losses - Thermal mass is not always beneficial in relation to thermal comfort and energy consumption - Phase change materials reduce internal temperature fluctuations in buildings, providing better thermal comfort to occupants - Trombe walls are aesthetically appealing, but in regions with mild winters and hot summers, overheating problems may outweigh the winter benefits.		are still controversial - Improvement of thermal inertia can be achieved by using materials with high density, such as concrete or rammed earth or by using phase change materials - The process of autoclaving concrete requires significant energy consumption		
Electric vehicles for land transport	36	Electromobility is being adopted across a range of land transport options including light-duty vehicles, trains and some heavy-duty vehicles, suggesting no physical constraints	37–41	Current dominant battery chemistry relies on minerals that may face supply constraints, including lithium, cobalt, and nickel. Regional supply/availability varies. Alternative chemistries exist; recycling may likewise alleviate critical material concerns. Similar supply	42,43	No major changes in land use for the vehicle. Potential increases in land use for electricity generation (especially solar, wind or hydropower) and mineral extraction, but may be partially offset by a decrease in land use for fossil fuel production; likely lower land use than

				constraints may exist for some renewable electricity sources (e.g., solar) required to support EVs. May reduce critical materials required for catalytic converters in ICEVs (e.g., platinum, palladium, rhodium)		crop-based biofuels, or technologies with higher electricity use (e.g., those based electrolytic hydrogen)
Electrification industry[#]	[44–46]	The potential for direct or indirect (e.g., green hydrogen) electrification in industry varies across different industrial sectors and applications.	[46,47]	Due to potentially very high electricity demands for chemicals and steel electrification may be difficult in existing plants with low access to inexpensive electricity. Industry may relocate to regions with bountiful solar and wind resources.	NE[*]	Electrification does not increase the direct land-use of industry itself.
Enhanced weathering	[48–53]		[52–57]	Silicate rock formations, silicate rock dust stockpiles, C&D waste	[53], LE	Existing croplands, co-deployable with afforestation/reforestation/BECCS/biochar

Note: [#] Electrification in industry includes direct and indirect (e.g., with hydrogen) electrification. [*] It is pretty obvious that electrification does not increase land use of industry itself, which may explain why effects of electrification in industry on land use are not discussed in the literature.

	Environmental-ecological							
	Air pollution		**Toxic waste, ecotoxicity and eutrophication**		**Water quantity and quality**		**Biodiversity**	
	Line of sight	**Role of context**	**Line of sight**	**Role of context**	**Line of sight**	**Role of context**	**Line of sight**	**Role of context**
Solar energy	58	Minimal effects in manufacturing	58,59	Low when recycled properly	58		60	Concerns in protected areas
Integrating sectors, strategies and innovations	61–68	Integrating across urban land use and spatial planning, electrification of urban energy systems, district heating and cooling networks, urban green and blue infrastructure and waste management has positive impacts on improving air quality	69	Level of improvement depends on the demands of low carbon development on materials and urban metabolism performance	70–77	Level of improvement depends on the interaction and inclusion of low carbon development options that reduce impacts on water use and increases quality, including water use efficiency, demand management and recycling	78,79	Level of improvement depends on urban metabolism and biophilic urbanism towards urban areas that regenerate natural capital
Envelope improvement	80–90	Eliminate major sources (both direct and indirect) of poor air quality (indoor and outdoor)	80–90	As a result of the reduced consumption of natural resources and reduced air pollution levels	80–90	Reduced energy demand can lead to reduced water consumption for thermal cooling at energy production facilities	80–90	Reduced air pollution levels achieved by mitigation actions improves biodiversity
Electric vehicles for land transport	91–96	Elimination of tailpipe emissions. If powered by nuclear or renewables, large overall improvements in air pollution. Even if powered partially by	97–100	Some toxic waste associated with mining and processing of metals for battery and some renewable electricity supply chains (production and disposal)	101–103	May increase or decrease water footprint depending on the upstream electricity source	LE	Potential biodiversity issues related to electricity generation; however fossil fuel supply chains also adversely impact biodiversity; net effect is unknown

		fossil fuel electricity, tailpipe emissions tend to occur closer to population and thus typically have larger impact on human health than powerplant emissions; negative air quality impacts may occur, but only in fossil fuel heavy grids						
Electrification industry	47,104	Electrification reduces air-pollution as the use and combustion of fuels are avoided.	47,104	No direct effects on toxic waste and ecotoxicity have been found. NO_x emissions will decrease with less combustion.	105	Hydrogen production requires water but the water that forms when hydrogen is oxidised (e.g., in hydrogen steelmaking) can be recycled. Water quantities for industrial hydrogen demands are modest.	NE**	No direct effects on biodiversity from electrification of industrial processes.
Enhanced weathering	LE	Air-blown rock dust, reduction in NOx emissions	NE		NE		NE	

Note: ** It is pretty obvious that electrification of industrial processes does not affect biodiversity, which may explain why this effect is not discussed in the literature.

	Technological feasibility					
	Simplicity		Technological scalability		Maturity and technology readiness	
	Line of sight	Role of context	Line of sight	Role of context	Line of sight	Role of context
Solar energy	106	Globally simple	107	Globally scalable	108	Globally mature
Integrating sectors, strategies and innovations	109–114	Depends on the ability to initiate and learn from experimentation and the ability to support GHG emission reductions based on both structural, behavioural and lifestyle changes	65,115–129	Depends on the mitigation options integrated, the stage of urban development and typology of the urban area with certain contexts providing additional opportunities over others	130–138	Multiple technologies are available for integration while further depending on context and the level of integration, e.g. energy-driven urban design for optimizing the impact of urban form on energy infrastructure
Envelope improvement	19,24,27,29,31,32,34,35 ,139–149	There are different envelope measures with different levels of simplicity. Building integrated concepts (such as insulation or phase change materials) are very simple. Reducing infiltration is achieved by replacing windows and doors, and sealing cracks, the simplicity of this varies by building. Other concepts such as greenery systems can be more complicated	19,24,27,29,31,32,34,35 ,139–149	From a facade to a building to a multifamily house	19,24,27,29,31,32,34,35 ,139–149	- Insulation is very well known technology, however sustainable materials need future research - A step forward is the use of transparent insulation materials for building energy savings and daylight comfort - Vertical greenery systems are still being controversial depending on the climate and materials - Phase change materials can be organic or inorganic, each type with their advantages

						and disadvantages
Electric vehicles for land transport	150	Fewer engine components; lower maintenance requirements than conventional vehicles; potential concerns surrounding battery size/weight, charging time, and battery life	36,41,151–154	Widespread application already feasible; some limits to adoption in remote communities or long-haul freight; at large scale, may positively or negatively impact electric grid functioning depending on charging behaviour and grid integration strategy	36,154,155	+ Technology is mature for light duty vehicles; - Improvements in battery capacity and density as well as charging speed required for heavy duty applications
Electrification industry	156	There are varying levels of technological simplicity across options.	46,47,157,158	Technologies area scalable across industrial subsectors but access to inexpensive electricity is important.	44,159–161	Varies across sub-sectors due to complexity and heterogeneity of heavy industry
Enhanced weathering	49,56	Straight forward, utilises existing technology	53	Upscaling is potentially straight forward, infrastructure (e.g. road rail) already in place for handling harvests of equivalent mass	162	Components of technology are mature, including the application of minerals to land, however commercially operating supply chains for CO_2 removal are immature, longitudinal field scale demonstrations are required

	Economic			
	Costs in 2030 and long term		**Employment effects and economic growth**	
	Line of sight	**Role of context**	**Line of sight**	**Role of context**
Solar energy	[107]	Low and declining	[163]	Globally beneficial
Integrating sectors, strategies and innovations	[62,164–171]	Provides cost benefits that increases with a portfolio approach for cost-effective, cost-neutral and re-investment options with evidence across different urban typologies as well as cost reduction options with urban form	[171–176]	Increases based on the speed that the mitigation option triggers economic decoupling with a positive impact on employment and local competitiveness
Envelope improvement	[84,88,177–184 185–207]	There are many individual examples of cost-effective deep retrofits involving the envelope improvement, however few studies calculate the costs of deep retrofits at large scale. Literature tends to agree that cost-effective deep retrofits are not universally applicable for all cases and at a large scale, among all measures this is the most expensive one. Due to high upfront costs, the key factor determining the feasibility is coupling the retrofit with business-as-usual improvement and applying an industrialized one-stop-shop approach. Given a long payback time, energy price dynamics and a discount rate play especially a large role.	[84,88,177–184 185,186,195–204,187,205–207,188–194]	Positive and negative direct and indirect effects associated with lower energy demand and possible reductions in energy prices, energy efficiency investments, lower energy expenditures, and fostering innovation. Improvements in labour productivity.
Electric vehicles for land transport	[36,152–154]	Life cycle costs for electric vehicles are anticipated to be lower than conventional vehicles by 2030; high confidence for light duty vehicles; lower	LE	Some grey studies exist on employment effects of electric vehicles; however, the peer-reviewed literature is not well developed

		confidence for heavy duty applications		
Electrification industry	44,46,160,161,208,209	Increased production costs, but impact vary widely across industrial subsectors and applications. Some markets, notably automakers, seem willing to pay the price premium	46,47,210	Competitive advantages may lead to shifts in the location of production but there is no evidence that electrification will lead to fewer or more jobs within industry itself.
Enhanced weathering	53	Developed countries: 160-190 USD tCO_2^{-1} removed; developing countries cheaper: 55-120 USD tCO_2^{-1}	NE	Potential to increase employment in mining, transport sectors

	Socio-cultural					
	Public acceptance		Effects on health & wellbeing		Distributional effects	
	Line of sight	Role of context	Line of sight	Role of context	Line of sight	Role of context
Solar energy	211–223	High upfront costs and long payback periods may be barriers for adoption; not feasible for all households (e.g., apartments, rental houses)	224	Globally beneficial	225	High upfront costs deter adoption for low income groups and in developing countries, despite low total costs. Distribution of costs and benefits change as a function of design choices.
Integrating sectors, strategies and innovations	226–236	Contexts that involve a participatory approach towards urban transformation with a shared understanding of future opportunities and challenges are enablers. Public acceptance increases with citizen engagement and citizen empowerment as well as an awareness of the co-benefits	61,64,237–241	The scope of low carbon urban development measures provides significant potential for co-benefits for public health and wellbeing	166,236,242–248	Level of improvement depends on integrating issues of equity, inclusivity and affordability, safeguarding urban livelihoods, access to basic services, lowering the energy bill, addressing energy poverty, and improving public health
Envelope improvement	81,83,84,177,179,184,249–289	Perceived as increased comfort and status, with limited concerns for heritage or aesthetic values in regions with higher living standards	81,83,84,177,179,184,249–289	Health benefits through better indoor air quality, energy/fuel poverty alleviation, better ambient air quality, and elimination of the heat island effect. Envelope improvement with inadequate ventilation may lead to the sick building syndrome	81,83,84,177,179,184,249–289	Result in lower energy bills, avoiding the “heat or eat” dilemma, alleviating energy/fuel poverty and improving energy security. Furthermore, these interventions have positive impacts to the energy systems, by improving the primary

				symptoms; ventilation is crucial in creating healthy indoor environmental conditions, which result in (mainly respiratory) health benefits		energy intensity of the economy and reducing dependence on fossil fuels, which for many countries are imported
Electric vehicles for land transport	290–292	Growing public acceptance, especially in some jurisdictions (e.g., majority of light duty vehicle sales in Norway are electric), but wide differences across regions; range anxiety remains a barrier among some groups	293	No major impacts; some potential for reduced noise, which can improve wellbeing of city residents but may adversely affect pedestrian safety	294,295	Higher vehicle purchase price and access to off-road parking limits access to some disadvantaged groups; potentially insufficient infrastructure for adoption in rural communities (initially); air quality improvements may disproportionately benefit disadvantaged groups, but may also shift some impacts onto communities in close proximity to electricity generators
Electrification industry	161,208	Public acceptance is not so relevant for electrification of industry itself, but less pollution is expected to be welcomed. Public acceptance for large scale wind and solar production is important but not in scope here.	47,104	Cleaner work environment is possible through some applications and less air-pollution is an important co-benefit of electrification.	210,296,297	Introducing new sustainable basic materials production processes could increase production costs but, given the small fraction of consumer cost based on materials, are expected to translate into minimal cost increases for final consumers.

Enhanced weathering	298,299	In US and UK, public support for limited trials with careful monitoring, public concern if it involved opening new mines	NE	Respirable dust means caution required during application, not a barrier to implementation	55	

	Institutional					
	Political acceptance		Institutional capacity & governance, cross-sectoral coordination		Legal and administrative feasibility	
	Line of sight	Role of context	Line of sight	Role of context	Line of sight	Role of context
Solar energy	300	Opposed by fossil interests	301	Need support for rapid scale up in developing countries	302	Electricity market reforms required
Integrating sectors, strategies and innovations	303–309	Depends on the GHG reduction or climate neutrality target that is set as well as support from participatory processes	67,310–329	Depends on the ability to form partnerships to overcome barriers, including technology development, rule-setting and demonstration, capacity to manage transitions, establishing integrated departments and funding schemes for low carbon urban development, implementing system innovations and aligning system actors, engaging in policy learning among cities and implementing supportive policy mixes	330,331	Depends on the capacity to implement relevant policy instruments in an integrated way and leverage multilevel policies as relevant
Envelope improvement	332–341	Not perceived as a priority policy for energy efficiency in buildings by many policy makers in particular in warm climate and in developing countries. Policy makers are neutral to	332–341	Very often building performance and envelopment improvements require very specific technical capabilities. In some countries building codes are established at local level, with gaps in	332–341	Building codes are difficult to enforce, often compliance is based on design and no check is carried out when in use. In use energy may be much higher than calculated energy. Envelop improvement in particular for

		the technology implemented to improve the building energy performances. Incentives are often used to promote insulation in residential buildings		governance and coordination between different levels of government		existing building are difficult to verify also in the case on public subsidies
Electric vehicles for land transport	36,41	Varied political support for deployment in different regions of the world	36,41	Coordination needed between transport sector (including vehicle manufacturers; charging infrastructure) and power sector (including increased generation and transmission; capacity to handle demand peaks). Institutional capacity is variable	36,41	Compatible with urban low emission zones; grid integration may require market and regulatory changes
Electrification industry	44,46,161,208,209	There are no studies that specifically study the political acceptance of industrial electrification but from policy-oriented studies it can be inferred that this is an enabler.	208,209,342	Industrial deep decarbonisation including electrification is a relatively new field with a need for building institutional and governance capacities	NE	
Enhanced weathering	343	But non-climate co-benefits may be valuable in terms of the policy 'demand pull' for CDR	LE		NA - All components of the supply chain are already practiced commercially	May not be limiting for natural silicate rock given existing protocols for fertiliser, potentially limiting for alkaline wastes/by-products

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Table

Table 2. Line of sight of the assessment of the feasibility of the options presented in Figure 1, and an overview of the extent to which the feasibility of the options may differ across context (e.g., region), time (e.g., 2030 versus 2050), and scale (e.g., small versus large).

	Geophysical					
	Physical potential		**Geophysical recourses**		**Land use**	
	Line of sight	**Role of context**	**Line of sight**	**Role of context**	**Line of sight**	**Role of context**
Solar energy	1	Limited in higher latitudes	2	Not limited by materials	3	Limited in urban areas
Integrating sectors, strategies and innovations	4,5	Ability to reduce pressures on physical land resources for urban areas	6–14	Depends on lowering the material demands for urban development with opportunities for considering materials with lower GHG impacts and selection of urban development plans with lower material demands	5,15,16	Increases with the role of urban land use and spatial planning in low carbon development and the relevance of brownfield urban development for the project
Envelope improvement	17–35	- Not applicable in historical/heritage buildings where modifications to facade are difficult - Transparent insulation materials provide the advantages of insulation materials including also the advantages of being able to use daylight - Green Roofs enhance building aesthetics and	17–35	- Conventional insulation materials are derived from petrochemical substance, but new sustainable insulation materials have been developed - Environmental impacts of green roofs depends on the selection of efficient and sustainable components. Green	17–35	NA

		reduce heat gains and losses - Thermal mass is not always beneficial in relation to thermal comfort and energy consumption - Phase change materials reduce internal temperature fluctuations in buildings, providing better thermal comfort to occupants - Trombe walls are aesthetically appealing, but in regions with mild winters and hot summers, overheating problems may outweigh the winter benefits.		walls are still controversial - Improvement of thermal inertia can be achieved by using materials with high density, such as concrete or rammed earth or by using phase change materials - The process of autoclaving concrete requires significant energy consumption		
Electric vehicles for land transport	36	Electromobility is being adopted across a range of land transport options including light-duty vehicles, trains and some heavy-duty vehicles, suggesting no physical constraints	37–41	Current dominant battery chemistry relies on minerals that may face supply constraints, including lithium, cobalt, and nickel. Regional supply/availability varies. Alternative chemistries exist; recycling may likewise alleviate critical material concerns. Similar supply constraints may exist for some renewable electricity sources (e.g., solar) required to support EVs. May reduce critical materials required for catalytic converters in	42,43	No major changes in land use for the vehicle. Potential increases in land use for electricity generation (especially solar, wind or hydropower) and mineral extraction, but may be partially offset by a decrease in land use for fossil fuel production; likely lower land use than crop-based biofuels, or technologies with higher electricity use (e.g., those based electrolytic hydrogen)

				ICEVs (e.g., platinum, palladium, rhodium)		
Electrification industry[#]	[44–46]	The potential for direct or indirect (e.g., green hydrogen) electrification in industry varies across different industrial sectors and applications.	[46,47]	Due to potentially very high electricity demands for chemicals and steel electrification may be difficult in existing plants with low access to inexpensive electricity. Industry may relocate to regions with bountiful solar and wind resources.	NE[*]	Electrification does not increase the direct land-use of industry itself.
Enhanced weathering	[48–53]		[52–57]	Silicate rock formations, silicate rock dust stockpiles, C&D waste	[53], LE	Existing croplands, co-deployable with afforestation/reforestation/BECCS/biochar

Note: [#] Electrification in industry includes direct and indirect (e.g., with hydrogen) electrification. [*] It is pretty obvious that electrification does not increase land use of industry itself, which may explain why effects of electrification in industry on land use are not discussed in the literature.

	Environmental-ecological							
	Air pollution		**Toxic waste, ecotoxicity and eutrophication**		**Water quantity and quality**		**Biodiversity**	
	Line of sight	**Role of context**	**Line of sight**	**Role of context**	**Line of sight**	**Role of context**	**Line of sight**	**Role of context**
Solar energy	[58]	Minimal effects in manufacturing	[58,59]	Low when recycled properly	[58]		[60]	Concerns in protected areas
Integrating sectors, strategies and innovations	[61–68]	Integrating across urban land use and spatial planning, electrification of urban energy systems, district heating and cooling networks, urban green and blue infrastructure and waste management has positive impacts on improving air quality	[69]	Level of improvement depends on the demands of low carbon development on materials and urban metabolism performance	[70–77]	Level of improvement depends on the interaction and inclusion of low carbon development options that reduce impacts on water use and increases quality, including water use efficiency, demand management and recycling	[78,79]	Level of improvement depends on urban metabolism and biophilic urbanism towards urban areas that regenerate natural capital
Envelope improvement	[80–90]	Eliminate major sources (both direct and indirect) of poor air quality (indoor and outdoor)	[80–90]	As a result of the reduced consumption of natural resources and reduced air pollution levels	[80–90]	Reduced energy demand can lead to reduced water consumption for thermal cooling at energy production facilities	[80–90]	Reduced air pollution levels achieved by mitigation actions improves biodiversity
Electric vehicles for land transport	[91–96]	Elimination of tailpipe emissions. If powered by nuclear or renewables, large overall improvements in air pollution. Even if powered partially by	[97–100]	Some toxic waste associated with mining and processing of metals for battery and some renewable electricity supply	[101–103]	May increase or decrease water footprint depending on the upstream electricity [source]	LE	Potential biodiversity issues related to electricity generation; however fossil fuel supply chains also adversely impact

		fossil fuel electricity, tailpipe emissions tend to occur closer to population and thus typically have larger impact on human health than powerplant emissions; negative air quality impacts may occur, but only in fossil fuel heavy grids		chains (production and disposal)				biodiversity; net effect is unknown
Electrification industry	47,104	Electrification reduces air-pollution as the use and combustion of fuels are avoided.	47,104	No direct effects on toxic waste and ecotoxicity have been found. NO_x emissions will decrease with less combustion.	105	Hydrogen production requires water but the water that forms when hydrogen is oxidised (e.g., in hydrogen steelmaking) can be recycled. Water quantities for industrial hydrogen demands are modest.	NE**	No direct effects on biodiversity from electrification of industrial processes.
Enhanced weathering	LE	Air-blown rock dust, reduction in NOx emissions	NE		NE		NE	

Note: ** It is pretty obvious that electrification of industrial processes does not affect biodiversity, which may explain why this effect is not discussed in the literature.

	Technological feasibility					
	Simplicity		**Technological scalability**		**Maturity and technology readiness**	
	Line of sight	**Role of context**	**Line of sight**	**Role of context**	**Line of sight**	**Role of context**
Solar energy	106	Globally simple	107	Globally scalable	108	Globally mature
Integrating sectors, strategies and innovations	109–114	Depends on the ability to initiate and learn from experimentation and the ability to support GHG emission reductions based on both structural, behavioural and lifestyle changes	65,115–129	Depends on the mitigation options integrated, the stage of urban development and typology of the urban area with certain contexts providing additional opportunities over others	130–138	Multiple technologies are available for integration while further depending on context and the level of integration, e.g. energy-driven urban design for optimizing the impact of urban form on energy infrastructure
Envelope improvement	19,24,27,29,31,32,34,35,139–149	There are different envelope measures with different levels of simplicity. Building integrated concepts (such as insulation or phase change materials) are very simple. Reducing infiltration is achieved by replacing windows and doors, and sealing cracks, the simplicity of this varies by building. Other concepts such as greenery systems can be more complicated	19,24,27,29,31,32,34,35,139–149	From a facade to a building to a multifamily house	19,24,27,29,31,32,34,35,139–149	- Insulation is very well known technology, however sustainable materials need future research - A step forward is the use of transparent insulation materials for building energy savings and daylight comfort - Vertical greenery systems are still being controversial depending on the climate and materials - Phase change materials can be organic or inorganic, each type with their advantages and disadvantages

Electric vehicles for land transport	150	Fewer engine components; lower maintenance requirements than conventional vehicles; potential concerns surrounding battery size/weight, charging time, and battery life	36,41,151–154	Widespread application already feasible; some limits to adoption in remote communities or long-haul freight; at large scale, may positively or negatively impact electric grid functioning depending on charging behaviour and grid integration strategy	36,154,155	+ Technology is mature for light duty vehicles; - Improvements in battery capacity and density as well as charging speed required for heavy duty applications
Electrification industry	156	There are varying levels of technological simplicity across options.	46,47,157,158	Technologies area scalable across industrial subsectors but access to inexpensive electricity is important.	44,159–161	Varies across sub-sectors due to complexity and heterogeneity of heavy industry
Enhanced weathering	49,56	Straight forward, utilises existing technology	53	Upscaling is potentially straight forward, infrastructure (e.g. road rail) already in place for handling harvests of equivalent mass	162	Components of technology are mature, including the application of minerals to land, however commercially operating supply chains for CO_2 removal are immature, longitudinal field scale demonstrations are required

	Economic			
	Costs in 2030 and long term		**Employment effects and economic growth**	
	Line of sight	**Role of context**	**Line of sight**	**Role of context**
Solar energy	[107]	Low and declining	[163]	Globally beneficial
Integrating sectors, strategies and innovations	[62,164–171]	Provides cost benefits that increases with a portfolio approach for cost-effective, cost-neutral and re-investment options with evidence across different urban typologies as well as cost reduction options with urban form	[171–176]	Increases based on the speed that the mitigation option triggers economic decoupling with a positive impact on employment and local competitiveness
Envelope improvement	[84,88,177–184 185–207]	There are many individual examples of cost-effective deep retrofits involving the envelope improvement, however few studies calculate the costs of deep retrofits at large scale. Literature tends to agree that cost-effective deep retrofits are not universally applicable for all cases and at a large scale, among all measures this is the most expensive one. Due to high upfront costs, the key factor determining the feasibility is coupling the retrofit with business-as-usual improvement and applying an industrialized one-stop-shop approach. Given a long payback time, energy price dynamics and a discount rate play especially a large role.	[84,88,177–184 185,186,195–204,187,205–207,188–194]	Positive and negative direct and indirect effects associated with lower energy demand and possible reductions in energy prices, energy efficiency investments, lower energy expenditures, and fostering innovation. Improvements in labour productivity.

Electric vehicles for land transport	36,152–154	Life cycle costs for electric vehicles are anticipated to be lower than conventional vehicles by 2030; high confidence for light duty vehicles; lower confidence for heavy duty applications	LE	Some grey studies exist on employment effects of electric vehicles; however, the peer-reviewed literature is not well developed
Electrification industry	44,46,160,161,208,209	Increased production costs, but impact vary widely across industrial subsectors and applications. Some markets, notably automakers, seem willing to pay the price premium	46,47,210	Competitive advantages may lead to shifts in the location of production but there is no evidence that electrification will lead to fewer or more jobs within industry itself.
Enhanced weathering	53	Developed countries: 160-190 USD tCO_2^{-1} removed; developing countries cheaper: 55-120 USD tCO_2^{-1}	NE	Potential to increase employment in mining, transport sectors

	Socio-cultural					
	Public acceptance		Effects on health & wellbeing		Distributional effects	
	Line of sight	Role of context	Line of sight	Role of context	Line of sight	Role of context
Solar energy	211–223	High upfront costs and long payback periods may be barriers for adoption; not feasible for all households (e.g., apartments, rental houses)	224	Globally beneficial	225	High upfront costs deter adoption for low income groups and in developing countries, despite low total costs. Distribution of costs and benefits change as a function of design choices.
Integrating sectors, strategies and innovations	226–236	Contexts that involve a participatory approach towards urban transformation with a shared understanding of future opportunities and challenges are enablers. Public acceptance increases with citizen engagement and citizen empowerment as well as an awareness of the co-benefits	61,64,237–241	The scope of low carbon urban development measures provides significant potential for co-benefits for public health and wellbeing	166,236,242–248	Level of improvement depends on integrating issues of equity, inclusivity and affordability, safeguarding urban livelihoods, access to basic services, lowering the energy bill, addressing energy poverty, and improving public health
Envelope improvement	81,83,84,177,179,184,249–289	Perceived as increased comfort and status, with limited concerns for heritage or aesthetic values in regions with higher living standards	81,83,84,177,179,184,249–289	Health benefits through better indoor air quality, energy/fuel poverty alleviation, better ambient air quality, and elimination of the heat island effect. Envelope improvement with inadequate ventilation may lead to the sick building syndrome symptoms; ventilation is crucial in creating healthy indoor	81,83,84,177,179,184,249–289	Result in lower energy bills, avoiding the “heat or eat” dilemma, alleviating energy/fuel poverty and improving energy security. Furthermore, these interventions have positive impacts to the energy systems, by improving the primary energy intensity of the economy and reducing dependence on fossil

				environmental conditions, which result in (mainly respiratory) health benefits		fuels, which for many countries are imported
Electric vehicles for land transport	290–292	Growing public acceptance, especially in some jurisdictions (e.g., majority of light duty vehicle sales in Norway are electric), but wide differences across regions; range anxiety remains a barrier among some groups	293	No major impacts; some potential for reduced noise, which can improve wellbeing of city residents but may adversely affect pedestrian safety	294,295	Higher vehicle purchase price and access to off-road parking limits access to some disadvantaged groups; potentially insufficient infrastructure for adoption in rural communities (initially); air quality improvements may disproportionately benefit disadvantaged groups, but may also shift some impacts onto communities in close proximity to electricity generators
Electrification industry	161,208	Public acceptance is not so relevant for electrification of industry itself, but less pollution is expected to be welcomed. Public acceptance for large scale wind and solar production is important but not in scope here.	47,104	Cleaner work environment is possible through some applications and less air-pollution is an important co-benefit of electrification.	210,296,297	Introducing new sustainable basic materials production processes could increase production costs but, given the small fraction of consumer cost based on materials, are expected to translate into minimal cost increases for final consumers.
Enhanced weathering	298,299	In US and UK, public support for limited trials with careful monitoring, public concern if it involved opening new mines	NE	Respirable dust means caution required during application, not a barrier to implementation	55	

	Institutional					
	Political acceptance		Institutional capacity & governance, cross-sectoral coordination		Legal and administrative feasibility	
	Line of sight	Role of context	Line of sight	Role of context	Line of sight	Role of context
Solar energy	300	Opposed by fossil interests	301	Need support for rapid scale up in developing countries	302	Electricity market reforms required
Integrating sectors, strategies and innovations	303–309	Depends on the GHG reduction or climate neutrality target that is set as well as support from participatory processes	67,310–329	Depends on the ability to form partnerships to overcome barriers, including technology development, rule-setting and demonstration, capacity to manage transitions, establishing integrated departments and funding schemes for low carbon urban development, implementing system innovations and aligning system actors, engaging in policy learning among cities and implementing supportive policy mixes	330,331	Depends on the capacity to implement relevant policy instruments in an integrated way and leverage multilevel policies as relevant
Envelope improvement	332–341	Not perceived as a priority policy for energy efficiency in buildings by many policy makers in particular in warm climate and in developing countries. Policy makers are neutral to the technology implemented to improve the building	332–341	Very often building performance and envelopment improvements require very specific technical capabilities. In some countries building codes are established at local level, with gaps in governance and	332–341	Building codes are difficult to enforce, often compliance is based on design and no check is carried out when in use. In use energy may be much higher than calculated energy. Envelop improvement in particular for existing

		energy performances. Incentives are often used to promote insulation in residential buildings		coordination between different levels of government		building are difficult to verify also in the case on public subsidies
Electric vehicles for land transport	36,41	Varied political support for deployment in different regions of the world	36,41	Coordination needed between transport sector (including vehicle manufacturers; charging infrastructure) and power sector (including increased generation and transmission; capacity to handle demand peaks). Institutional capacity is variable	36,41	Compatible with urban low emission zones; grid integration may require market and regulatory changes
Electrification industry	44,46,161,208,209	There are no studies that specifically study the political acceptance of industrial electrification but from policy-oriented studies it can be inferred that this is an enabler.	208,209,342	Industrial deep decarbonisation including electrification is a relatively new field with a need for building institutional and governance capacities	NE	
Enhanced weathering	343	But non-climate co-benefits may be valuable in terms of the policy 'demand pull' for CDR	LE		NA - All components of the supply chain are already practiced commercially	May not be limiting for natural silicate rock given existing protocols for fertiliser, potentially limiting for alkaline wastes/by-products

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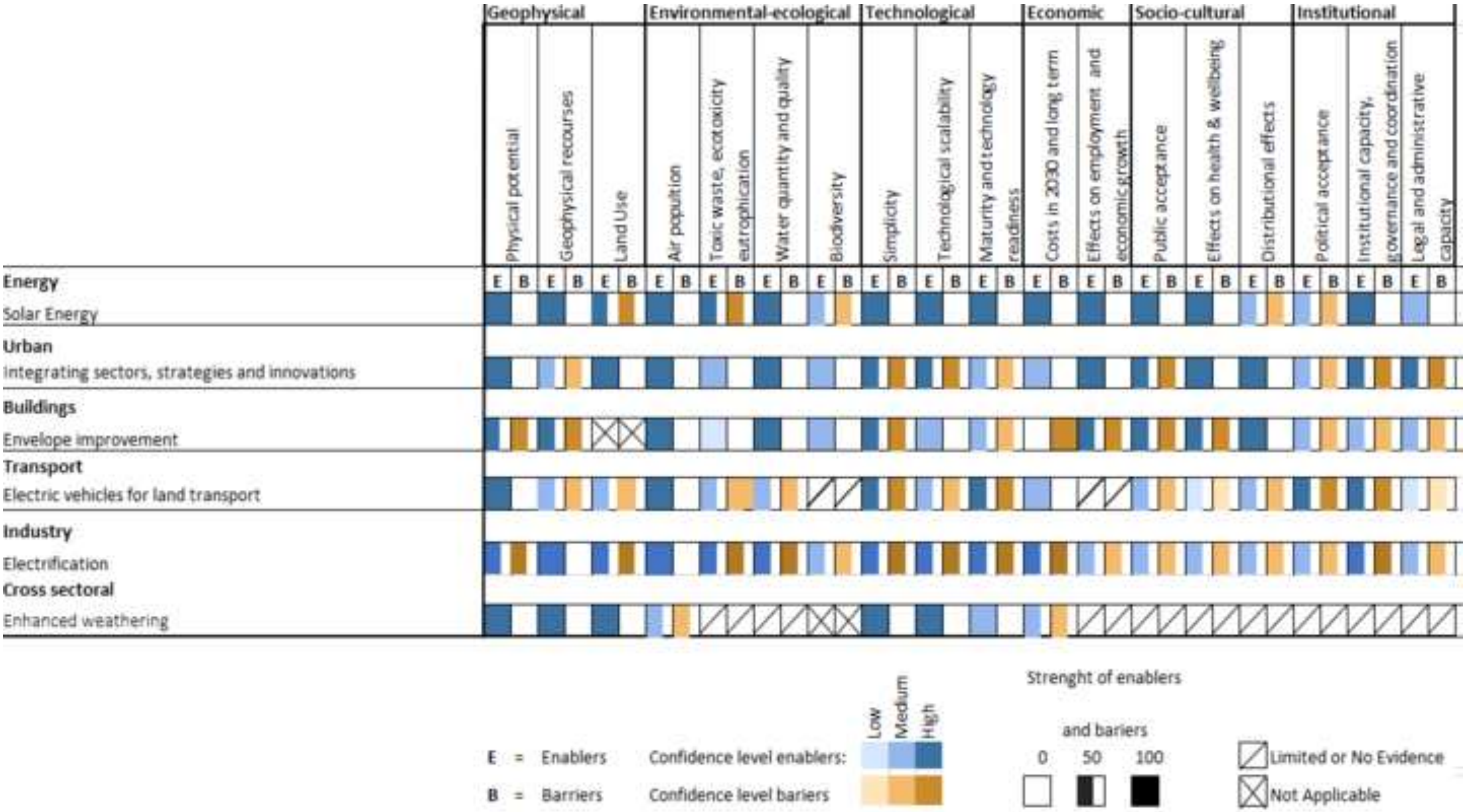
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Biodiversity
Simplicity
Technological scalability
Maturity and technology readiness
Costs in 2030 and long term
Effects on employment and economic growth
Public acceptance
Effects on health & wellbeing
Distributional effects
Political acceptance
Institutional capacity, governance and coordination
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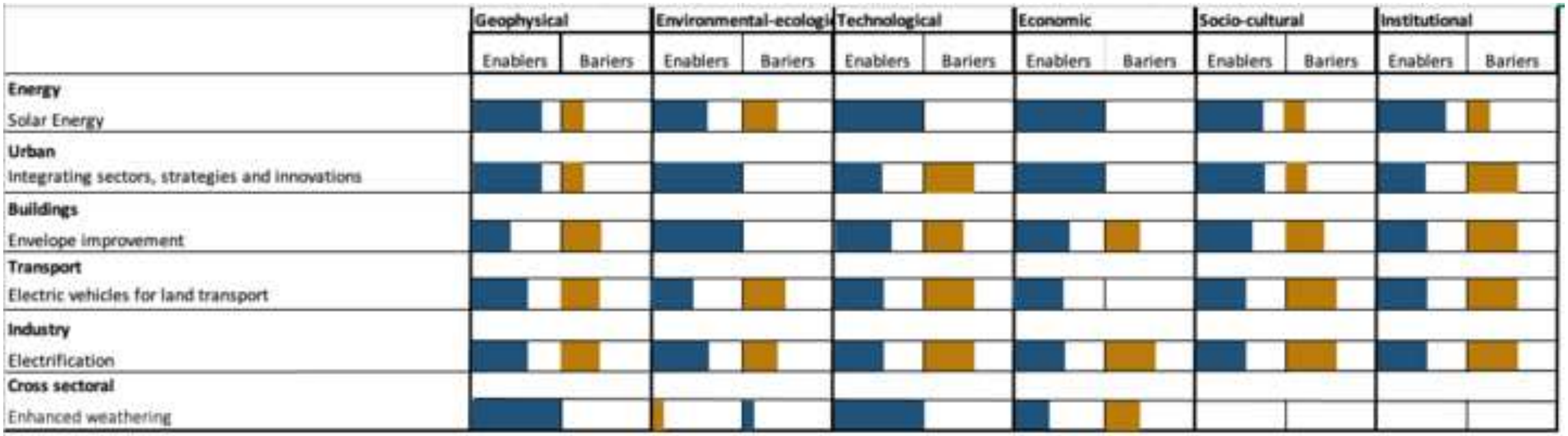
Figure 2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