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Measuring the Co-Benefits of Climate Change Mitigation

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multiple benefits, co-benefits, adverse side effects, risks, co-impacts, quantification, social cost-benefit analysis, multicriteria analysis, integrated assessment models, decision support

Abstract

Co-benefits rarely enter quantitative decision-support frameworks, often because the methodologies for their integration are lacking or not known. This review fills in this gap by providing comprehensive methodological guidance on the quantification of co-impacts and their integration into climate-related decision making based on the literature. The article first clarifies the confusion in the literature about related terms and makes a proposal for a more consistent terminological framework, then emphasizes the importance of working in a multiple-objective–multiple-impact framework. It creates a taxonomy of co-impacts and uses this to propose a methodological framework for the identification of the key co-impacts to be assessed for a given climate policy and to avoid double counting. It reviews the different methods available to quantify and monetize different co-impacts and introduces three methodological frameworks that can be used to integrate these results into decision making. On the basis of an initial assessment of selected studies, it also demonstrates that the incorporation of co-impacts can significantly change the outcome of economic assessments. Finally, the review calls for major new research and innovation toward simplified evaluation methods and streamlined tools for more widely applicable appraisals of co-impacts for decision making.

Contents

1. INTRODUCTION

1.1. Rationales: Going Beyond the Direct Financial Assessment of Mitigation Options

Co-benefits have become a major topic in climate and energy discourses. They are often cited in the context of climate-related decision making as factors that can significantly change the outcomes of direct cost-benefit evaluations (1–3). However, although often referred to and argued with, they are rarely measured, quantified, or monetized, and even less frequently do they enter the quantitative decision-making frameworks applied to climate change. They often just remain at the rhetorical or discourse levels, even though their inclusion may substantially influence the outcomes of decision processes.

Ideally, for any decision, a full stream of costs and benefits of all impacts should be considered. In practice, however, cost-benefit and cost-effectiveness analyses of climate change mitigation measures and policies capture a fairly narrow range of direct consequences—see, for instance, the cost methodology discussion in Sathaye & Shukla's review (4) of greenhouse gas (GHG) costing. The analyses typically leave aside a broader range of indirect consequences. When indirect consequences do get included, these are typically limited to less than a handful of the most mainstream benefits, such as air pollution reduction and related health impacts. Furthermore, the lack of consistent methodologies for their quantification and summation sometimes leads to criticisms of double counting.

The main purpose of the review, therefore, is to aid in filling this gap: We provide comprehensive methodological guidance for the quantification of indirect costs and benefits and their integration into decision-making frameworks.

However, because of confusions detected in the literature, we first clarify the meaning of several concepts and their relationship to each other as these influence the consistency of their incorporation into decision-making frameworks. These concepts include multiple nonclimate benefits, ancillary benefits, co-impacts, co-costs, disbenefits, transaction costs, trade-offs, spillover effects, externalities, and others. There is also a degree of confusion stemming from determining what the main impact is and what the co-impacts are. For instance, although nonclimate benefits are often referred to as co-benefits, in fact, the majority of these nonclimate benefits are likely to be the primary reasons for pursuing interventions.

In this article, as in the Intergovernmental Panel on Climate Change's (IPCC's) fifth assessment report (5), the terms co-benefits and adverse side effects are used when discussing the positive and negative side effects of mitigation policies and technologies, with the term co-impact synthetizing the two. For reasons detailed below, including the fact that the same impact can be a benefit or an adverse side effect, we suggest the more ubiquitous use of the term co-impact.

Finally, although the article's primary focus is methodological, it also attempts to shed light on the overall importance of co-benefits and co-costs. Because of the lack of general literature on this subject, the issue is illustrated using selected case studies.

1.2. Aims and Scope

As stated above, the purpose of this article is to provide a comprehensive methodological guidance for the conceptualization, identification, and quantification of co-benefits (co-impacts) and their inclusion in decision-support frameworks, based on the review of the literature.

Owing to the infancy of the related sciences, it is not possible to provide a comprehensive, all-encompassing methodology for the assessment of co-impacts, and thus the review aims to provide a walking stick for understanding the related concepts, to suggest a framework for quantifying co-impacts, and to discuss how co-impacts can be incorporated into various decision-making frameworks.

More specifically, the article is organized as follows:

1. First, the article disentangles the confusion in the literature about the various terms used related to co-benefits, explains their relationship to each other and to climate-related decision making, creates a map of the various related concepts, and proposes an alternative framework for discussing these terms.
2. Second, the relationships between the different impacts are discussed, and the validity of the usage of the co prefix in these concepts is appraised. While doing so, we argue for considering co-benefits in a multiple-objective/multiple-impact framework rather than in a single-purpose co-benefit one and explain the importance of planning and welfare assessment using such an approach.
3. Next, the article focuses on the evaluation of co-benefits. Within this, the taxonomies of various co-benefits that enter the climate discourse are discussed in relationship to various mitigation strategies.
4. Then, the literature is reviewed to provide a list of key co-benefits and the methodologies for their quantification and monetization. A framework is proposed that can be used for the identification of relevant co-benefits and their interrelationships; this framework also minimizes the risks of double counting and facilitates comprehensive coverage of the issues.
5. Three methods are reviewed that are used for the integration of quantified co-impacts into decision-making frameworks.

6. Because the field of comprehensively evaluated co-impacts is new, it is not possible to draw general, robust conclusions about the relative and general importance of co-benefits. Nevertheless, some observations are made about the overall significance of co-benefits and about the categories that might be particularly important on the basis of some selected cases.
7. Finally, the major gaps in related knowledge are identified, and a research and innovation agenda is proposed for progress on how to automatically integrate co-impacts into traditional decision-making frameworks.

With regard to the scope and purpose of the conceptual overview and organizing framework of co-effects of climate change mitigation, this article spans the entire range of co-impacts. When progressing to the methodological review, there is a focus on the co-benefits of climate change mitigation, and within that, many case studies discuss sustainable energy options, including improved energy efficiency and the increased use of renewable energy sources, to enable more consistent in-depth coverage.

2. THE RELEVANCE OF CO-BENEFITS FOR CLIMATE CHANGE MITIGATION

Climate change mitigation policies and measures are primarily aimed at reducing the emissions of GHGs relative to what would happen in the absence of the policy or measure (baseline). It can be thus understood that the primary benefits of these policies are the welfare effects of lower GHG emissions with respect to the baseline. These benefits are the avoided costs of the impacts of climate change. The marginal cost of one additional unit of GHG in the atmosphere (and thus the marginal benefit of not emitting that unit) is known as the social cost of carbon. In theory, the social cost of carbon provides a benchmark for assessing the cost-effectiveness of GHG mitigation policies and measures (1).

However, decades of experience in the design, implementation, and assessment of climate policies and measures have demonstrated that these also have consequences on areas other than climate and thus can serve diverse policy purposes and social priorities. There is evidence that mitigation measures have a range of positive human health, ecosystem functioning, macroeconomic, social, and/or equity side effects that in some cases outweigh the importance of climate change mitigation benefits. These have been often referred to as co-benefits or ancillary benefits.

Similarly, climate-related investments and policies can have adverse or negative co-impacts, referred to as disbenefits, co-costs, risks, or adverse side effects. For example, shifting to nuclear power plants reduces emissions in the power sector but introduces other risks. Increased use of energy from biomass helps reduce GHG emissions (to the extent the biomass pool is managed sustainably) but can, in some cases, have adverse side effects in terms of increased competition on agricultural land or loss of biodiversity.

The presence of co-impacts (co-benefits and adverse side effects) is not surprising because, in most cases, GHG emissions cannot be reduced with everything else being equal. Low-carbon technologies often differ from high-carbon ones (e.g., wind or solar versus thermal power plants) not only by their emissions per unit of output, but also by many other characteristics (labor intensity, capital intensity, etc.). As a result, installing low-carbon technologies typically has systemic impacts well beyond GHG emission reductions. Furthermore, reducing emissions via energy demand management typically requires changes in the behaviors of households and firms that also have complex outcomes. In fact, an absence of co-impacts is probably the exception much more than the rule.

Increased understanding of the policy relevance of co-benefits has been parallel to the development of climate change science since the first IPCC assessment reports were released in the early 1990s (6), although it has been reported that a similar notion was previously discussed in the 1985 joint United Nations Environment Programme/World Meteorological Organization/International Conference for Science climate change conference and by Crutzen & Graedel's contribution to the 1986 book *Sustainable Development of the Biosphere* (7). An important milestone in that process was an Organisation for Economic Co-operation and Development experts' workshop (8) held in the year 2000, which gathered substantial input and helped frame the importance of the issue. The related statement by Krupnick et al. (9) is still up-to-date and defines with clear precision the significance of the issue under discussion:

> A great deal is at stake . . . . If these ancillary benefits are significant. . .then perhaps the development and implementation of climate policy should be altered. At the very least, knowing that the possibly high cost of climate change mitigation might be largely offset by ancillary benefits could speed up and spread the commitment to action as well as implementation itself. On the other hand, if these effects are "small" relative to the other costs or the benefits of reducing GHGs, perhaps they can be safely ignored in the debate over climate change mitigation policy—at least from the perspective of efficiency—simplifying an already too complex debate. (p. 1)

This idea is graphically depicted for the case of energy efficiency in buildings in **Figure 1**. In theory (10), the socially efficient level of emissions reduction is reached when the marginal cost of abating one additional unit of pollutant equals the marginal benefit of reducing that unit. In the case of climate change, the most evident benefits of abating GHG emissions are the primary benefits of mitigation (i.e., avoided social cost of carbon). If only these are considered (MB_{PB}), then the optimal abatement effort is set at Q^*_1, whereas if both primary and co-benefits are accounted for ($MB_{PB+CoBe}$), a more ambitious abatement optimum (Q^*_2) is obtained.

In addition, co-benefits can contribute to tackling two important barriers faced by policy makers when deciding on the implementation of ambitious climate policies. First, it has been suggested that policy makers are far more concerned about short-term mitigation costs than with the

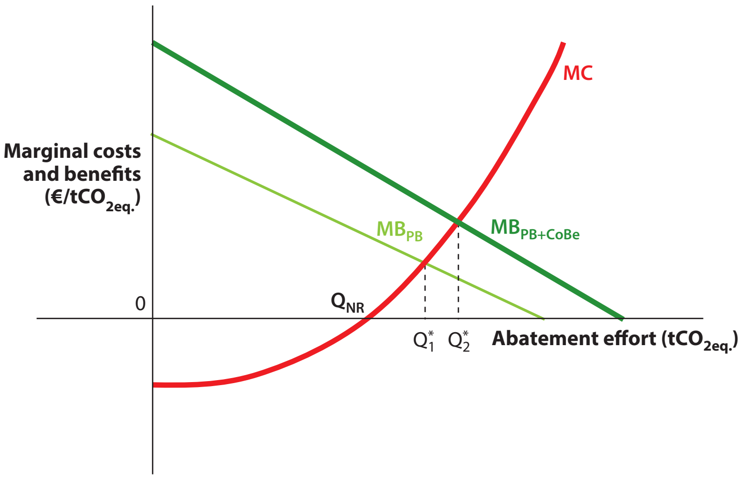

Figure 1

The optimal pollution level hypothesis applied to the case of co-benefits of climate change mitigation. Figure modified from Pearce (6) and Turner (10). Abbreviations: MB_{PB}, marginal primary benefits of mitigation; $MB_{PB+CoBe}$, marginal primary benefits and co-benefits of mitigation are considered; MC, marginal cost of pollution; Q, optimal abatement effort when only primary benefits are considered; Q, optimal abatement effort when co-benefits are considered; Q_{NR}, no-regret abatement effort level.

long-term balances of costs and benefits. This effect, known as loss aversion (6), stems from the perception that, even if strong mitigation is started in the present, its effects on global temperatures would be considerably delayed in time (in fact, at an intergenerational timescale). Because most co-benefits, unlike the primary benefit, are enjoyed typically at regional or local scales, are closer to the agents bearing the mitigation costs (typically the taxpayers and/or the consumers), and have more immediate welfare effects (11), they provide incentives for decision makers to engage in more resolute climate action. Thus, climate benefits are reaped by future generations, and co-benefits mostly refer to the welfare effects enjoyed by present generations, so it can be argued that co-benefits (when the net results of the co-impacts are positive) contribute to bypassing the apparent intergenerational conflict of interests through which climate policies have been criticized based on equity grounds. This happens when a decision with positive effects in terms of climate change mitigation is made because of more pressing issues affecting the present life of citizens. Such is the case, for instance, of the EU's roadmap for a low-carbon economy by 2050 (12), where the substantial investments required for the transition are partially justified by the expected creation of new jobs, the forecast reduction of energy imports, and the foreseeable gains in air quality and health. Second, there is another particular feature of the global climate that prevents a coordinated international action against climate change. Because climatic stability currently is an underprovided global public good (a public good is one whose consumption is nonrivaled and nonexcludable), climate change can be taken as an updated example of the tragedy of the commons (13). As the primary benefits of a mitigated climate change are spread globally, irrespective of whether a nation is contributing to the mitigation or not, individual actors have an incentive to not participate, so that certain nations bear mitigation costs and others just benefit from the mitigation efforts (1). In such a context, as illustrated by the vagaries of the international climate negotiations since the early 1990s, finding a global agreement on climate mitigation is difficult. Here, co-benefits, or a positive net effect of the co-impacts, thus play an important role as they provide additional incentives to engage in mitigation actions, new entry points for mitigation policy making, and perhaps even incentives to formalize these actions through commitments to international agreements (14). Dolšak (15), for example, argues that it is precisely the domestic co-benefits of reduced air pollution that explain implementation of domestic mitigation policies in the face of a global collective action problem caused by a weak global regime with limited compliance mechanisms.

As the discussion above suggests, co-benefits are relevant not only for the economics of mitigation, but also for the politics of climate decision making. Rogers et al. (16) suggest that net co-benefit approaches can help remove barriers to domestic policy change through linkage to climate changes and by providing a focal point for groups advocating for climate policies. Partly in recognition of this fact, there is a growing tendency to embed climate mitigation policy within a larger framework of low-carbon development strategies and plans, which explicitly invoke co-benefits as the motivation for action. In China, for example, local implementation of climate plans is strongly tied to local incentives for energy efficiency (17–21). India's National Action Plan on Climate Change explicitly states that it is driven by co-benefits, understood as development actions that also bring climate gains (22, 23). In Brazil, a robust climate policy is strongly associated with domestic breakthroughs in forest policy (24, 25). This logic is also at work in the developed world. For example, Gore & Robinson (26) argue that expansion of municipal-scale climate action in the United States is often justified by the existence of co-benefits.

3. MAPPING CONCEPTS AND TERMINOLOGIES RELATED TO CO-BENEFITS

There is a wide spectrum of concepts that are related to co-benefits in the literature; many of them are used either interchangeably or with major overlaps, but the high number of terms and

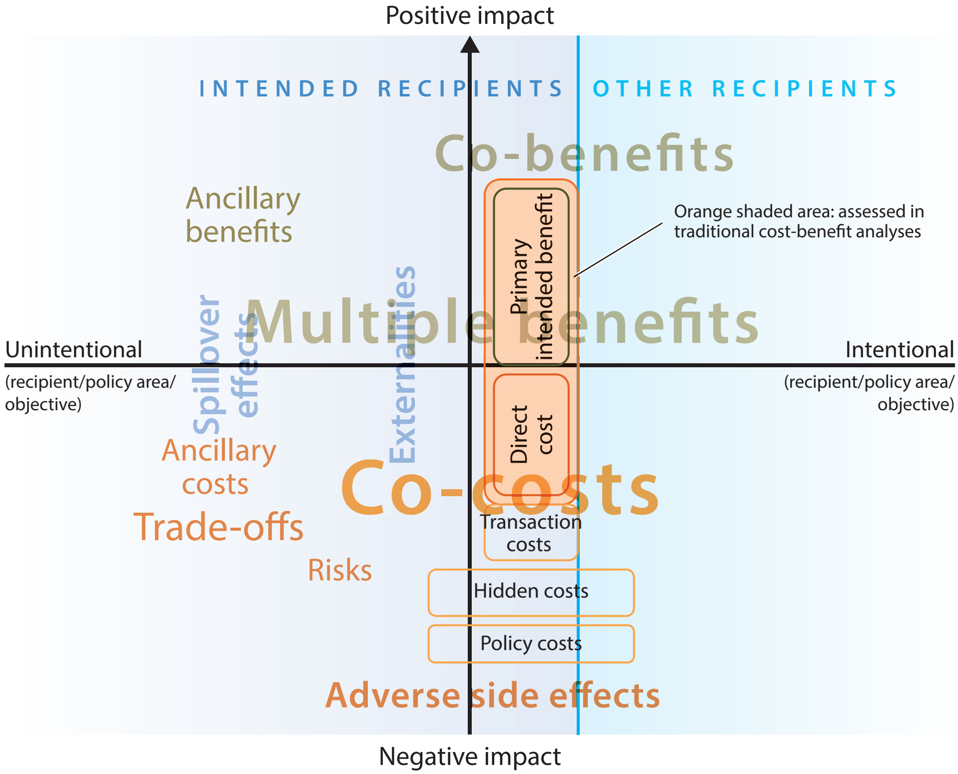

Figure 2

Schematic map of different terms used in connection with co-impacts. The shaded area refers to the domain of typical cost-benefit analyses of policies or mitigation options. The horizontal axis is divided by the intention of the objective/policy area/recipient. Many definitions are used in different ways by different authors, and thus this is only a schematic diagram that characterizes the key axes along which the main definitions differ: intentionality and positive versus negative impacts.

their relationship to each other can get confusing. **Figure 2** organizes these often overlapping concepts, as they are used in the literature, in a rough map to clarify their relationship. Note that on the map the distance from each term to the origin or the distance between two terms does not affect the size or importance of the effect/term. The only element that matters on the map is the position of each term relative to the two axes (i.e., on the positive or negative side, or straddling the axes).

Because of the overlapping meanings and definitions, there can be several ways to organize and conceptualize these terms. During the review of past literature concerning these definitions, two parameters seemed crucial in mapping their attributed meaning and relationship to each other: (*a*) the positive and/or negative nature of the effect and (*b*) the degree of intentionality with which multiple effects are considered. The first is self-evident, but the second requires somewhat more explanation. The co-benefits discussion has been characterized by a growing sense that the multiple effects of policies and actions need to be more fully considered in mitigation plans. Thus, there has been a progression from an early effort at noting that some climate policies have substantial impacts on other objectives and indeed can be entirely justified on the basis of those objectives, such as the health gains of reducing indoor pollution, proceeding to an effort to develop mechanisms of explicitly and intentionally designing policies around multiple objectives. See Streimikiene &

Balezentis (27) for an example of the multi-objective ranking of climate change mitigation policies and measures in Lithuania.

Intentionality has played an important role in earlier co-benefit discourses, as reflected in the terminologies used (28, 29). Reflecting recent trends in this subject, we recommend de-emphasizing intentionality in this discussion; but to organize and understand the literature to date, we review the role it has played. Intentionality is related to the intended impact and sector, but also to stakeholder groups/beneficiaries, such as countries; see, for example, the spillover effect or ancillary versus co-benefits as used in the IPCC's third assessment report (28) and in Jochem & Madlener (29). Spillover effects are defined (1) as the consequences of domestic- or sector-specific mitigation actions on other (i.e., not originally intended) jurisdictions or sectors. They may be positive or negative and take the form of carbon leakage, effects on trade, and transfer of innovation and technologies.

Figure 2 lays out various terms on the axes of positive and negative effects and intentionality. The figure indicates in the middle shaded area the costs and benefits that are traditionally and typically conducted in the vast majority of evaluations of climate actions: direct costs and primary direct benefits. All of these costs and benefits occur to the same group of stakeholders/recipients (even though the correct use of cost-benefit analysis would require consideration of all costs or benefits, not just the direct ones, incurring to all affected parties). The same group, however, often also incurs transaction costs, such as those related to gathering information, finding the alternative technology, monitoring and verification, and others as well as those borne by project developers through the development of complex legal arrangements (see, for instance, 30). Although transaction costs are technology and policy-context specific, we recommend that they are taken into account—and minimized whenever possible—in the design, implementation, and assessment of policy instruments (31).

There are also often hidden costs, occurring to the same stakeholders as the direct costs and sometimes beyond the intended beneficiaries. Such costs would include a slightly modified service such as what arises when incandescent lamps are replaced by fluorescent ones, resulting in a changed color rendering.

When policies are being implemented, they have implementation costs, and thus it is not sufficient to consider merely the investment costs and benefits that occur to the actor who makes the investment as a result of the policy. These policy costs are often borne by a wider group of society than the immediate beneficiary of the investment (such as through the sale of renewable energy or profits through energy savings).

The remaining terms in **Figure 2** cover the domain of co-impacts, i.e., the various additional nondirect costs and benefits. Co-benefits are shown as occupying the upper right quadrant, using its definition in the IPCC's third assessment report (1, p. 812) as the "benefits of policies implemented for various reasons at the same time, acknowledging that most policies designed to address greenhouse gas mitigation have other, often at least equally important, rationales (e.g., related to objectives of development, sustainability, and equity)." This, somewhat confusingly phrased, definition focuses on simultaneous effects of a policy on different outcomes and signals a high level of intentional action. By contrast, ancillary benefits are placed in the upper left quadrant, defined as "Policies aimed at some target, e.g., climate change mitigation, may be paired with positive side effects" (1, p. 809), signaling low intentionality. However, as many other authors do not make an explicit distinction between co- and ancillary benefits, we placed co-benefits crossing over the intentionality axis. Other related terms, such as nonclimate benefits and nonenergy benefits (1, 32, 33), are also used as alternatives to co-benefits. Spillover effects are firmly on the unintentional side of the figure and can be either positive or negative. Unintentional negative effects are ancillary costs (8), ancillary impacts (1), co-costs (34), adverse side effects (5), risks (35), externalities (9), and trade-offs (36) and often have meanings that overlap. Everything that has negative effects can also be referred to as co-cost or adverse side effect (the latter is used in this article) and everything with a positive side effect is considered a co-benefit for the rest of this review.

There are other issues that complicate the identification of an effect in such taxonomy. First, in practice, it is not very easy to determine what the primary aim of the policy is, and thus what is a co-benefit to another benefit. The trend, therefore, is toward consideration of multiple benefits and less toward defining what is primary and what is secondary. For instance, energy-efficiency policies are not begun for the sake of saving energy itself, but these always serve additional purposes, such as emissions reduction or energy cost reduction.

In fact, climate policy and climate investment,[1] except in a few countries, rarely takes place for the sole purpose of mitigating climate change, but most typically these serve other primary purposes, with the co-benefit being climate mitigation. This is especially true in developing countries, where basic development objectives often strongly outweigh the importance of climate objectives for the allocation of scarce resources. In such cases and in the vast majority of climate policies and investments, it is difficult to discuss the co-benefits of climate policies because the emphasis is on the co-benefits of development (or other) policies that need to be considered for climate policy.

Owing to this blurred nature of primary and secondary benefits, combined with the other reasons detailed above, for a proper assessment of the indirect costs and benefits (co-benefits), ideally a multiple-objective and multiple-impact framework needs to be used, assessing the full range of welfare effects. This recognizes that policies, actions, and investments often have multiple purposes and impacts in several areas. Such a framework also recognizes another challenge: Often it is not possible to determine a priori if an effect is positive or negative, in part, because contextual factors are extremely salient to this determination, thus affecting whether it is treated as a co-benefit or an adverse side effect. For example, the net employment implication of a mitigation policy may be positive or negative, or both. For example, the same co-impact can be positive for one stakeholder (such as increased employment in the wind turbine or solar panel construction industry as a result of a policy that supports the use of renewable energy) and negative for another one (such as decreased employment in the companies that build coal- or gas-fired thermal power plants as a result of the same renewable energy policy). Similarly, a climate policy can be very beneficial for the country implementing the policy, such as low-emission, advanced transportation technologies replacing older polluting vehicles in developed countries but may be much more negative for other countries. For example, if the emissions-intensive vehicles withdrawn from the market in the developed country considered above are sold at discount prices in developing countries, they will contribute to increased pollution- and injury-related health risks there (35). Therefore, categorizing an effect as a co-benefit (or any other term in the positive domain of **Figure 2**) or as an adverse side effect (or any other term in the negative domain of **Figure 2**) is often challenging or misleading or hides the complexity of the co-impacts.

As a result of using a multiple-objective/multiple-impact framework in an ideal assessment, the distinction between the positive and negative effects, as well as intentionality and other modalities that are traditionally distinguished among these terms, become less important with trends toward an integrated treatment, and thus this review advocates for the future usage of these more general terms. Along with these trends, the expression multiple benefits has been adopted by the International Energy Agency (37), although this still introduces an initial bias toward the positivity of impacts. Other key initiatives, such as the *Global Energy Assessment* (2), took this approach as well.

[1]The term climate investment is used to refer to investments made for the purpose of, or in relation to, climate change mitigation.

The IPCC (1) also has been using the terms co-impact and ancillary impacts as a way to refer to both the positive and negative side effects of mitigation policies. From scientific and analytical perspectives, it is more correct to use co-impacts to ensure a neutral treatment of the different effects, but in the political and occasional policy literature, use of co-benefits or multiple benefits may still be justified owing to a specific focus on leveraging the positive impacts.

Distinguishing co-impacts or co-benefits from multiple impacts/benefits is mostly justified for analytical or political purposes when, for instance, it is difficult to evaluate the benefits in a full multi-objective welfare framing, or politically one benefit becomes a primary one, or one policy goal is singled out for certain (analytical) purposes. Although ideally a proper assessment of all co-impacts is needed in climate and energy policy and political discourses, co- or multiple benefits are often emphasized as distinct from the adverse side effects, and thus these are also terms that are likely to keep their ubiquitous use in the literature.

In summary, in this review, we use the terms co-benefits and multiple benefits for the positive co-impacts, and adverse side effects for the negative ones, following expert agreements for a consistent use of terminology for the fifth assessment report of the IPCC (5). Co-impacts encompass the entire range and often substitute for the longer expression of co-benefits and adverse side effects in the sections below.

4. IDENTIFYING AND TAXONOMIZING CO-IMPACTS

4.1. Challenges to the Identification and Consideration of Co-Impacts

After laying out the background on the different related terms and concepts as used in the literature, this section provides a guide for starting with the assessment of co-impacts. It includes (*a*) a discussion of some general challenges to the assessment of co-impacts, (*b*) a methodological framework that helps with the identification of the concrete co-impacts (as they occur for specific cases) and with the creation of a broad taxonomy, and (*c*) a more detailed discussion of individual co-impact groups.

In addition to the confusion over definitions discussed in Section 3, additional considerations complicate the conceptualization of co-impacts and their analysis that need to be carefully observed.

First, as mentioned above, a multiple-objective/multiple-impact framework is necessary for a sound evaluation of co-benefits. For example, the United Nations Environment Programme (38) has developed a framework built around a hierarchical criteria tree that contains multiple categories, such as financing, GHG mitigation, social (e.g., reducing inequity), environmental, climate impact, and political and institutional, e.g., improved governance. Also, the Government of Japan has developed a methodology for assessment of co-benefits in the context of Clean Development Mechanism (CDM) projects (39). Dubash et al. (40) have developed a decision-making approach for assessing various policy options on the basis of multiple objectives, such as growth, inclusion, local environment, and climate mitigation. However, all these efforts are in their infancy and have yet to be applied and tested thoroughly. Much of the existing literature, therefore, focuses on climate mitigation as the primary benefit rather than as one among multiple benefits.

Second, a rigorous analysis of co-benefits should be based on understanding the net welfare effect of a given policy, including the full range of interactions. However, conducting such a thorough analysis often carries too high an analytical burden for the practicality of implementation. Moreover, in developing countries that are often far from optimal policy frontiers, this level of analysis may be superfluous. For example, if climate mitigation also leads to local air pollution gains, in countries with advanced air pollution policies, this may not lead to additional welfare gains, but in most developing countries, it can safely be assumed that these gains will indeed lead to increased welfare gains because existing pollution levels are high. Hence, efforts to be more explicit about co-benefits and gauge the direction of effects, even if not the magnitude, can nonetheless be an aid to decision making.

A related point is that, even though welfare impacts should in theory be measured taking into account all the direct and indirect effects of the mitigation measure, in practice, however, mitigation costs are at best estimated using general equilibrium models.[2] Those should correctly take into account cross sectoral implications of a given mitigation policy (e.g., renewable development taking skilled labor out of other sectors, thereby reducing productivity in those sectors). But general equilibrium models typically do not include externalities and thus exclude a large range of environmental co-benefits. Another issue is that mitigation costs are often estimated using partial equilibrium models that do not even capture cross sectoral implications, let alone externalities.

Another related challenge is that, although in theory both costs and benefits of any given measure need to be computed, in practice, evaluation of costs and benefits are typically separated. In fact in cost-effectiveness approaches, an emission reduction goal is set, and then the mitigation paths that reach this emission reduction goal are compared in terms of their costs. Such a framework is not the best way to introduce co-benefits because the primary benefits of mitigation policies (i.e., avoided damages of climate change) are not computed.

The last two points are observations by authors and a community of experts but have not been extensively addressed by the scientific literature. The fourth point is that, even with a little or no net social welfare effect, impacts on individual groups of stakeholders can be very highly negative or positive and that the impacts of the same intervention/investment can vary for different stakeholders, highlighting the importance of the distributional effects. As a result, considering only net social welfare effects may be insufficient for a proper evaluation of the co-benefits in certain cases. A narrower unit of analysis (i.e., a particular stakeholder group) may be used as a complement to understand the co-benefits/co-costs for particularly important groups of society, such as the poorest. These distributive issues can also be internal to the analysis.

Fifth, beyond the public/private distinction, scale is important for understanding the groups affected by the co-benefits, e.g., for which groups the co-impacts are beneficial or detrimental. For instance, while an impact may be positive or negative at the local level (e.g., a wind turbine may have negative local co-impacts such as visual and noise), this could be the opposite at the national level (the national environmental implications of a wind turbine replacing fossil fuels are more positive). A policy may have positive co-impacts for one country, but negative co-impacts for another one (such as spill-over effects). For the evaluation of multiple benefits, the relevant groups of stakeholders at an appropriate scale need to be considered. For example, a policy operating at a municipal scale may have effects beyond that level, e.g., a major bus procurement program for public transport could bring down the costs of buses for the entire economy. These effects may also be transnational, and many of these scale effects are spillover effects.

4.2. Methodological Framework for the Identification and Taxonomization of Co-Impacts

Having acknowledged the existing challenges, a guide and taxonomy for the identification of the co-impacts for the consideration of indirect costs and benefits of climate change mitigation are

[2] General equilibrium models aim at representing the functioning of the economy as a whole, whereas partial equilibrium models focus only on a subset of markets (e.g., energy markets).

proposed. A taxonomy provides analysts with a menu to identify specific impacts for particular projects/policies. However, as discussed below, any such taxonomy is problematic because of the interactions among the different impacts, and thus this review proposes a methodological framework for the identification of the different co-impacts rather than an ultimate taxonomy, which has neither been created nor is perhaps possible because of the complexity of the task demands.

The categories in the taxonomy (**Table 1**) presented are our own but are based on previous reviews (e.g., 1, 37). It is more comprehensive than detailed: It does not aim to describe every single sector- or policy-specific typology of co-impacts located in the literature but suggests instead a few broad categories in which lower-order categories of co-benefits can be elaborated for concrete policy/action domains.

It is impossible to provide a taxonomy that covers distinct, independent co-impacts because many of them are interrelated, so there is no ideal ultimate taxonomy. Each has its own shortcomings. Different taxonomies reflect different purposes for the assessment of co-benefits.

Instead, we suggest that, for a comprehensive appraisal of co-impacts, the keys are to identify the causal relationships and interactions among the impacts and to distinguish co-impact end points and intermediate co-impacts that influence other outcomes. A relevant example of a similar approach used in a different field is the impact pathway methodology developed by the ExternE Project for the economic assessment of the impact of air pollution in the European Union. This methodology models the path followed by airborne pollutants from activities to emissions, concentration and exposure levels, physical impacts, and the monetary value of such impacts (for an example, see 38).

To aid such a thinking process, **Figure 3** suggests a conceptual framework for mapping different co-impacts and impact end points, for identifying their relationships to each other, and for following the impact chains and interactions that can take place, illustrated by energy-related mitigation options. These options are divided into technology-based solutions (energy efficiency and fuel switching including renewables) and nontechnological solutions (including changes in energy-use patterns, based on the adoption of lifestyles, values, and behaviors, as well as those targeting changes in land use, deforestation, and forest degradation, which significantly contribute to global emission levels).[3]

Figure 3 examines the diversity of multiple impacts of mitigation measures and illustrates that some of the categories often considered in the analysis of the co-benefits of climate change mitigation, which, in reality, refer to a range of end points that are used for the quantification of the overall welfare effects of mitigation policies. For instance, reducing the indoor and outdoor concentrations of air pollutants decreases the incidence of air pollution–related mortality and morbidity, but also enhances the provision of ecosystem services and plays roles in improving comfort levels and in enhancing workers' productivity.

5. METHODOLOGIES FOR QUANTIFICATION AND VALUATION OF CO-BENEFITS

Quantification, and most often monetization, of co-benefits can enable the integration of co-impacts into presently used decision-making frameworks, such as cost-benefit or cost-effectiveness analysis. Theoretically, for each of the co-benefits identified and described in the previous section, a monetary value could be estimated. To do so, the impact of the climate measure is first quantified

[3]It is estimated that 20% of global annual emissions of CO_2 is related to deforestation in tropical areas, which makes it the second largest contributor to climate change after the combustion of fossil fuels (41).

Table 1 Major categories of co-impacts of energy-based mitigation policies identified in the literature, with supporting evidence

Category of co-impact	Subcategory of impact	Description and supporting literature
Health impacts	Outdoor air pollution related	Energy-efficiency and fuel-switching measures typically reduce emissions of non-GHG pollutants harmful to human health (e.g., NH_3, SO_x, NO_x, PM, NMVOC, heavy metals, etc.), which has positive welfare effects in both developed (14, 42, 43) and developing economies (44, 45).
	Indoor air pollution related	Improved cooking stoves in developing countries reduce GHG emissions and alleviate the negative health effects of pollutants (e.g., CO, PM, black carbon) emitted by traditional biomass-based fuels (46, 47). Large-scale human health gains can be expected from the deployment of this technology as indoor air pollution is estimated to cause some 1.6 million premature deaths per year (48). Poor indoor air quality, related to the sick building syndrome, poses health risks to building occupants (49, 50) and can be potentially improved by energy-efficiency and some fuel-switching measures (51). Well-ventilated buildings reduce the presence of outdoor pollutants and can thus improve health and reduce allergies.
	Energy poverty related	Tackling energy poverty–related cold housing in developed and transition economies reduces excess winter mortality and morbidity (52–54). In addition to direct health impacts, cold housing has also negative mental health effects, e.g., increased stress and anxiety levels (55, 56). A large-scale deployment of renewable energy may result in an increase of energy prices and fuel poverty rates, as shown by Germany's energy transition (*Energiewende*) (57), which may increase cold-housing-related mortality and morbidity.
	Outdoor noise related	Climate investments in the buildings and transport sectors can provide additional protection against external noise, which has positive health effects as noise exposure is connected to a number of diseases and disorders (58). Nighttime noise may deserve particular attention because of the link between sleep disturbance and accidents (59).
	Transport and traffic related	Shifting from private car–based transport to active transport (e.g., cycling) and rapid transit/public transport is expected to reduce road traffic accident injuries, which globally kill 1.3 million people per year, and to prevent diseases related to obesity and physical inactivity, e.g., type-2 diabetes, heart disease, and some cancers (35, 60).
	Heat island related	More efficiently provided energy services can reduce the heat island effect and its related health impacts, i.e., heat-related deaths and illnesses (61) as well as those related to increased smog levels. Such changes can be especially important during extreme events, including heat waves, which are known to increase mortality rates (62, 63).
Access, affordability, and energy poverty	Access to modern energy services	Policies aimed both at alleviating energy poverty and controlling GHG emissions in developing countries have the potential to significantly improve the living conditions of over 2 billion people who lack access to modern energy services (64, 65). Such measures can provide significant gains in terms of security (e.g., fewer risks associated with biomass collection and combustion), comfort, productivity, and income-earning opportunities for the concerned population (2, 66).
	Affordability of energy services	In developed and transitional economies, residential energy-efficiency investments have the potential to significantly improve indoor thermal comfort levels and reduce the energy cost burden of households living in fuel/energy poverty (53, 67, 68). However, a rapid, large-scale deployment of renewables may have negatively affected the affordability of domestic energy services among low-income households, as shown by the *Energiewende*, energy transition, in Germany (57).

(*Continued*)

Table 1 ***(Continued)***

Category of co-impact	Subcategory of impact	Description and supporting literature
Comfort and living conditions	Thermal comfort	In developed and transition economies, improving the energy efficiency of buildings is reported to have positive effects in terms of the improved thermal comfort of building dwellers and users (69–71).
	Increased other comfort	Many energy-efficient alternatives represent advanced technologies compared to conventional ones and thus often have additional comfort impacts. For instance, high-efficiency lighting has much longer lifetimes, reducing replacement hassles, which is especially important for hard-to-reach fixtures, such as street lamps. The ventilation in high-performance buildings reduces indoor dust and thus cleaning needs.
	Exposure to noise	Residential energy efficiency and use of public transportation reduce human exposure to noise and mitigate GHG emissions (69, 72). However, some renewable technologies, e.g., wind turbines, increase noise levels, harming to some extent the well-being of the population living in surrounding areas (73–75).
Provision of ecosystem services		Ecosystems provide a wide range of provisioning, regulating, habitat, and cultural services (76) that can be potentially enhanced through changes in the emission levels of airborne pollutants (77) and by investing in activities that prevent deforestation and forest degradation, e.g., REDD+ (78), or harm through land-use changes, e.g., forest conversion for biofuel production (79). Renewables technologies, e.g., wind turbines, have an impact on biodiversity by killing birds, bats, and raptors. However, the turbine-related increase in avian mortality is several orders of magnitude below the fatality rates caused by vehicles, hunters, and cats (75).
Damage to building materials		Climate investments can reduce air pollution levels, which results in less damage to buildings and building materials (e.g., stonework erosion and blackening) that can be of particular concern for culturally significant places, e.g., historic buildings (80, 81).
Productivity	Performance of individuals and organizations	In public and commercial buildings, such as offices and schools, better temperature control, indoor air quality, and lighting positively influence the performance of users (82–84). The change in tropospheric ozone emissions from transport is demonstrated to have a significant impact on the productivity of agricultural workers (85). High-efficiency industrial processes improve competitiveness, and many energy-efficient processes also improve process efficiency/productivity.
	Crop yields	The productivity of agricultural land is also known to be affected by the atmospheric concentration of pollutants, e.g., the precursors of tropospheric ozone, NO_x, CO, CH_4, and NMVOCs (86). However, some airborne pollutants, e.g., SO_X, have a fertilizing effect on some crops that is beneficial for agricultural productivity (87).
Energy security		Energy security has been defined as the ability to guarantee an "uninterrupted provision of vital energy services" (2, p. 805) and includes the robustness, sovereignty, and resilience of energy systems. It has been estimated that most of the world's countries are vulnerable to energy security threats by at least one of these three concerns (2). Climate policies that reduce a nation's energy demands lessen the external risks associated with the consumption of imported energy, e.g., a sudden supply disruption and higher long-term energy costs (88), which are particularly relevant in in energy-dependent economies. For the same reason, energy-dependent countries may be tempted to apply measures that conflict with climate goals, e.g., switching from imported natural gas to domestic coal (2).

(*Continued*)

Table 1 (*Continued*)

Category of co-impact	Subcategory of impact	Description and supporting literature
Macroeconomic effects		Climate investments are expected to have positive macroeconomic impacts in terms of additional economic growth and employment creation when an economy is operating below its potential production level. Such positive net effects have been repeatedly reported for renewables and energy-efficiency investments in developed economies (89–93). In some developing countries, the production and commercialization of biomass-based energy both for local consumption (firewood) and export-oriented fuel (biofuel) are part of a thriving economic sector with the potential for additional gross domestic product growth and employment creation (94, 95). However, positive effects on employment are not permanent: In the case of renewable power in Germany, after a few years, job losses associated with the increase in the price of electricity may offset the investment-related positive effects of renewable power on employment (96). In the case of building energy efficiency in Hungary, growing permanent job losses in the energy generation and distribution sector may result in negative employment effects after two or three decades (97). Related to this, some climate investments result in unemployment in sectors like energy distribution, which may increase alcoholism, spousal abuse, and increased mental health problems among laid-off employees (8).

Abbreviations: CH_4, methane; CO, carbon monoxide; GHG, greenhouse gas; NH_3, ammonia; NMVOC, nonmethane volatile organic compounds; NO_x, nitrogen oxides; PM, particulate matter; REDD+, Reducing Emissions from Deforestation and Forest Degradation; SO_x, sulfur oxides.

in physical units (e.g., avoided tons of pollutants released, life years saved, number of additional full-time jobs created, etc.) before translation into a monetary value. For nonmarket goods and services, valuation is typically carried out by estimating the willingness to pay for benefits or the willingness to accept compensation for losses (e.g., replacement costs, avoided costs, contingent valuation, hedonic pricing, etc.). These methodologies, rooted in economic theory, have been applied in a number of research areas (98, 99). At the same time, there are major concerns and shortcomings related to the monetization of certain impacts, as economic valuation methodologies have been criticized with arguments related to the commodification of ecosystem services (100, 101) or to the ethical implications of differences between the value of life in countries and regions with different income levels (30, 102). Thus, when a physical metric (e.g., disability-adjusted life years) is a sufficient indicator for decision making, it may be safer to use these metrics for those more controversial impacts; see Stiglitz et al. (103) for a discussion about the convenience of physical indicators in sustainability assessments. **Table 2** synthesizes the key indicators and methodologies used for the quantification of different co-impacts of key climate change mitigation-related investments, separated by physical and monetary metrics.

A key caveat surrounding the quantification and valuation of co-benefits is that co-benefits are extremely context dependent (see, for example, the cases collected in **Table 3**). Although the direct costs of mitigation measures can more or less be determined (such as the cost of a wind turbine), its co-impacts are primarily context driven. In other words, the sign and size of their impact on welfare depend heavily on local circumstances as well as on how the policy is applied and on the conditions under which the intervention takes place. This has many consequences. For instance, it is difficult to make general judgments about the size of the impact of different co-benefits. Therefore, it is difficult to provide more generic, simplified methodologies for zero-order assessments of co-benefits.

Table 2 Indicators and methodologies used for the quantification of different co-impacts of key climate change mitigation-related investments, separated by physical and monetary metrics

Category of co-impacts	Subcategory of co-impacts	Physical indicator	Monetary indicator	Appraisal method	Examples and supporting literature
Health benefits	Outdoor air pollution related	Avoided cases Avoided hospital admissions Restricted activity days Years lived with disability Disability-adjusted life years (DALYs) Quality-adjusted life years Years of life lost	Avoided costs approach: cost of illness (cost per avoided case) Willingness to pay (WTP) for avoided case or death: value of a lost year and value of a statistical life (VSL)	Revealed preferences: avoided costs approach Stated preferences approach (contingent valuation)	For pollution-related health effects, the valuation is done in three stages (107): (*a*) calculation of changes in the concentration of air pollutants; (*b*) estimation of the human health response (e.g., cases or deaths avoided); and (*c*) valuation of avoided health impacts either through a cost of illness approach or through a WTP approach—see the evidence from developed (42, 108) and developing countries (44, 109). Providing universal access to electricity and clean cooking facilities would save 24 million DALYs by 2030 (2). For energy poverty–related health effects, the value of reduced excess winter mortality has been valued by VSLs and adult morbidity reduction using the avoided costs approach (e.g., reduced hospitalization and drugs costs); reductions in children's morbidity has been estimated through replacement costs or opportunity costs of child's caregiving, or the avoided cost of days away from school (110–112).
	Indoor air pollution related				
	Energy poverty related				
	Outdoor noise related				
	Transport and traffic related				
	Heat island related				
Energy poverty and distributional effects	Access to modern energy services	Additional kWh of quality energy (e.g., electricity) consumed Households with modern energy services (e.g., connected to the electricity grid)	WTP for an additional unit of quality energy (e.g., cost per kWh) or for having access to electricity (cost per household)	Consumer surplus estimation through stated preferences method (contingent valuation)	In developing countries, households' WTP for having access to electricity for lighting and TVs in the range \$0.10–0.40 per kWh, above the long-term supply costs of electricity estimated at \$0.05–0.12 per kWh (113). In the Philippines, a similar study reported a value of \$81 to \$150 per month and per household for the perceived benefits of gaining access to the electricity grid (114).
	Affordability of energy services	Decreased energy demand (e.g., kWh)	Per unit cost of energy (e.g., cost per kWh)	Energy prices	Estimates of reduced domestic energy costs owing to energy-efficiency investments can be estimated through energy prices (see 110, 115).
Comfort and living conditions	Thermal comfort	Increased indoor temperatures Increased percent of floor area heated	Forgone energy cost savings	Energy prices	Households, especially those in fuel/energy poverty, often heat their dwellings to suboptimal levels as an energy cost saving strategy. The value of this benefit can be estimated as the increased fraction of energy savings forgone (up to 50%), which is reaped as indoor temperature improvements after a thermal retrofit (see 110, 116).
	Exposure to external noise	Decibels (dBs) of external noise avoided	WTP to reduce exposure to external noise (e.g., cost per dB) Increase in the rental or sale price of properties (cost, percent)	Stated preferences (contingent valuation) Hedonic pricing	The contingent valuation of Bjørner (117) found an increasing WTP per dB dependent on the initial noise level—from €2 per dB at 55 dB to €10 per dB at 75 dB—for Copenhagen residents. Hedonic pricing studies of real estate market transaction prices in Switzerland and the Netherlands indicate that a building with energy-efficient characteristics yields a value ~3% higher than a conventional building (69, 118). This percentage reflects the capitalized value of future energy savings plus the value of co-benefits, e.g., protection against noise and general improvement in comfort.

Provision of ecosystem services		Hectares (ha) of ecosystem or units of ecosystem service flow (e.g., number of recreational visitors per year)	Cost per ha of ecosystem or unit of ecosystem service flow per year (e.g., cost per ha per year)	Market prices, stated preferences, and revealed preferences Benefit transfer and meta-analytical techniques	A whole range of valuation techniques is available, but a two-step approach is suggested: (*a*) estimating the change for the physical flow of a service (e.g., forest ha saved from acidification), and (*b*) application of per unit economic values (which can be sought in the growing body of literature) on the value of ecosystem services. These values are often very spatially heterogeneous and therefore context specific. However, researchers can use review papers (76, 119) that provide average values of the world's ecosystems in US dollars per ha per year employing benefit transfer and meta-analytical techniques.
Damage to building materials		Frequency of cleaning and maintenance of buildings	WTP for avoiding damage to building materials	Avoided cost approach (cleaning and restoration) Stated preferences (e.g., contingent valuation)	A contingent valuation study found that the WTP for an increase in the frequency (from 40 years to 10 years) of a hypothetical cleaning cycle of the UK's Lincoln cathedral was between 15 and 23 UK pounds per annum and per household of Lincoln and the surrounding area (120).
Productivity	Performance of individuals and organizations	Increase in labor productivity	Per unit labor costs	Market price of labor	Zivin & Neidell (85) found a 5.5% reduction in the productivity of agricultural workers in California's Central Valley per each 10 ppb increase in the concentration of tropospheric ozone. Accordingly, a 10 ppb reduction in surface ozone concentration would avoid US$700 million in labor costs across the United States.
	Crop yields	Increase in crop yields (percent)	Cost per unit of agricultural produce (e.g., cost per tonne)	Avoided cost and price of agricultural products	Estimated global losses in the agricultural production of soybean, wheat, and maize caused by surface ozone precursors (e.g., NMVOC and NO_x) caused by an amount (in year 2000 US$) of $12–35 billion annually (121).
Energy security		Units of imported energy avoided (e.g., oil barrels)	Cost per unit of imported energy (e.g., cost per oil barrel) WTP to secure the energy supply (e.g., cost per MWh)	Estimation of the macroeconomic external costs of energy imports Stated preferences (contingent valuation)	An energy security-related external cost of fossil-fuel consumption of between US$5 and US$15 per barrel has been estimated in the United States with the aim of suggesting an optimal consumption tax that compensates for the external effect of an insecure energy supply (88, 122). In Greece, a contingent valuation survey estimated that households are willing to pay a premium of between €4.5 and €12.7 per MWh on their electricity bills for securing the gas supply for electricity generation (123).

(*Continued*)

Table 2 (*Continued*)

Category of co-impacts	Subcategory of co-impacts	Physical indicator	Monetary indicator	Appraisal method	Examples and supporting literature
Macroeconomic effects		Percentage points of additional gross domestic product growth (%) Additional full-time equivalent (FTE) positions created	Monetary units per additional employment created (e.g., cost per FTE) Shadow price of labor costs in social cost-benefit analysis	Input-output (I/O) analysis, computable general equilibrium (CGE) models and macroeconomic models Analytical methods Opportunity costs of labor and public expenditures Stated preferences (choice experiment) Shadow pricing of labor costs	GDP and employment effects are often jointly quantified through I/O analysis (90, 92, 93, 97, 106). CGE and econometrically adjusted macroeconomic models capture more complex, dynamic effects, e.g., the crowding out of capital, materials, and labor (see 124, 125). The simpler, survey-based analytical method directly records the number of employees involved in a given industry, sector, or activity and only captures direct employment effects (126, 127). The monetary value of employment creation for a person finding a new job can be estimated through the opportunity cost of labor for the new employee, the opportunity cost of public expenditures used for promoting job creation (93, 106), or the stated preference methods that allow estimating a WTP for job creation (128). Pearce et al. (98) and the European Commission (129) suggest incorporating employment effects in social cost-benefit analysis through shadow pricing labor costs below the wage level when the project creates jobs for workers who would be unemployed had the project not taken place.

Abbreviations: kWh, kilowatt-hour.

Table 3 Quantitative assessment of the importance of co-benefits for selected case studies

Case number	Climate investment	Net direct B/C ratio and/or NPV[a,b]	Net B/C ratio or NPV including co-benefits	Importance of co-benefits as the % of direct or total benefits	Co-benefit categories in order of relevance (contribution to final results)	Source
1	Thermal retrofits of residential buildings in Ireland	B/C ratio: 1.7 (after 31 years at 5% discount rate)	B/C ratio: 2.0 (after 31 years at 5% discount rate)	Co-benefits are 75% of direct energy-saving benefits	Avoided excess winter mortality caused by energy poverty Comfort benefits Avoided emissions of SO_x, NO_x, and PM_{10} Avoided CO_2 emissions Avoided excess winter morbidity caused by energy poverty	110
		Social NPV: €1,111 Million (after 31 years at 5% discount rate)	Social NPV: €3,124 M (after 31 years at 5% discount rate)			
2	Thermal insulation of houses in low-income communities in New Zealand	B/C ratios: At 5% discount rate: 21.4 At 7% discount rate: 21.5 (after 30 years)	B/C ratios: At 5% discount rate: 4.8 At 7% discount rate: 4.8 (after 30 years)	Co-benefits are 350% of direct energy-saving benefits	Reduced hospital admissions Reduced days away from school Reduced days off work CO_2 savings	111
		Social NPV: At 5% discount rate: NZ$3,373 per household At 7% discount rate: NZ$3,275 per household (after 30 years)	Social NPV: At 5% discount rate: NZ$621 per household At 7% discount rate: NZ$502 per household (after 30 years)			
3	Thermal retrofits of residential buildings in Hungary	B/C ratios: MID scenario: 0.9 DEEP scenario: 0.9 (after 40 years at 5.5% discount rate)	B/C ratios: MID scenario: 2.6 DEEP scenario: 1.7 (after 40 years at 5.5% discount rate)	Co-benefits are between 97% (DEEP scenario) and 174% (MID scenario) of direct energy-saving benefits	Avoided emissions of non-GHG pollutants (SO_x, NO_x, PM, NMVOC, heavy metals, etc.) Comfort benefits Avoided excess winter mortality caused by energy poverty Avoided CO_2 emissions	115
		Social NPV (after 40 years at 5.5% discount rate): MID scenario: −€320 M DEEP scenario: −€3,125 M	Social NPV (after 40 years at 5.5% discount rate): MID scenario: €7,453 M DEEP scenario: €11,134 M			

(*Continued*)

Table 3 (*Continued*)

Case number	Climate investment	Net direct B/C ratio and/or NPV[a,b]	Net B/C ratio or NPV including co-benefits	Importance of co-benefits as the % of direct or total benefits	Co-benefit categories in order of relevance (contribution to final results)	Source
4	Renewable off-shore wind farms in Scotland	B/C ratios (after 15 years at 3% discount rate): 1-mile off-shore plant: 2.6 20-mile off-shore plant: 2.1	B/C ratios (after 15 years at 3% discount rate): 1-mile off-shore plant: 2.5 20-mile off-shore plant: 3.1	Co-benefits are between 53% (1-mile off-shore turbine) and 60% (20-mile off-shore turbine) of direct electricity output benefits	Displaced pollution is the only co-benefit category reported. It contains 5 subcategories (results not disaggregated): reduced mortality and morbidity, avoided ecological effects on water quality and heathlands, avoided damages to agricultural crops, avoided impact on historic buildings, and avoided CO_2 emissions.	148
		Social NPV (after 15 years at 3% discount rate): 1-mile off-shore plant: €21.8 M per turbine 20-mile off-shore plant: €30.4 M per turbine	Social NPV (after 15 years at 3% discount rate): 1-mile off-shore plant: €32.6 M per turbine 20-mile off-shore plant: €62.6 M per turbine			
5	Improved biomass cook-stoves in Mexico	NA	B/C ratio (after 14 years at a 10% discount rate): 10.2	Co-benefits are 83% of direct fuelwood saving benefits	Health impacts Environmental impacts (forest reserve preservation and GHG reduction) Job creation and income generation	149
			Social NPV (after 14 years at a 10% discount rate): $5,000 M			
6	Alternative use systems for remaining Ethiopian cloud forest	NA	Sustainable forest management Social NPV (at 40 years, carbon valued at $21 per ton C):[c] $20,360 per ha (10% discount rate) $36,631 per ha (5% discount rate) $44,900 per ha (3% discount rate)	Nonclimate benefits represent 92% of total benefits, whereas carbon storage benefits add 8% of the total.	Product values (timber, fuelwood, and coffee) Watershed services Carbon storage Coffee gene pool Pharmaceutical research	150
			Strict conservation Social NPV (at 40 years, carbon valued at $21 per ton C): $6,510 per ha (10% disc. rate) $12,246 per ha (5% disc. rate) $16,900 per ha (3% discount rate)	Nonclimate benefits represent 53% to 56% of total benefits, whereas carbon storage benefits add 44% to 47% of the total.	Carbon storage Watershed services Coffee gene pool Pharmaceutical research	

7	Mangrove conversion and conservation options in Thailand	NA	Conserved mangrove NPV at 30 years: $53–68 thousand per ha (at 6% discount rate) $73–94 thousand per ha (at 3% discount rate)	Nonclimate benefits represent 98% of total annual benefits, whereas carbon sequestration benefits comprise 2% of the total.	Storm protection Off-shore fisheries Shrimp revenues Carbon sequestration	151[d]
			Degraded mangrove/shrimp farming NPV at 30 years: $15–19 thousand per ha (at 6% discount rate) $24–31 thousand per ha (at 3% discount rate)	Nonclimate co-benefits represent 98% of total annual benefits, whereas carbon sequestration comprises 2% of the total.	Shrimp revenues Off-shore fisheries Carbon sequestration	

[a]Direct benefits refer to energy savings valued at energy prices.

[b]Abbreviations: B/C, benefit cost; DEEP scenario, deep retrofit scenario; GHG, greenhouse gas; *M*, million; MID scenario, middle-intensity retrofit scenario, NA, not applicable; NPV, net present value; PM_{10}, particulate matter with a diameter of 10 micrometers or less.

[c]The unit value of carbon storage, $21 per tonne of CO_2 carbon, is taken as the reference value for the analysis; however, the paper (150) also reports NPVs for alternative values of $58 and $129 per tonne of CO_2, which would substantially increase the NPVs and the importance of carbon.

[d]As reported in Turner et al. (152).

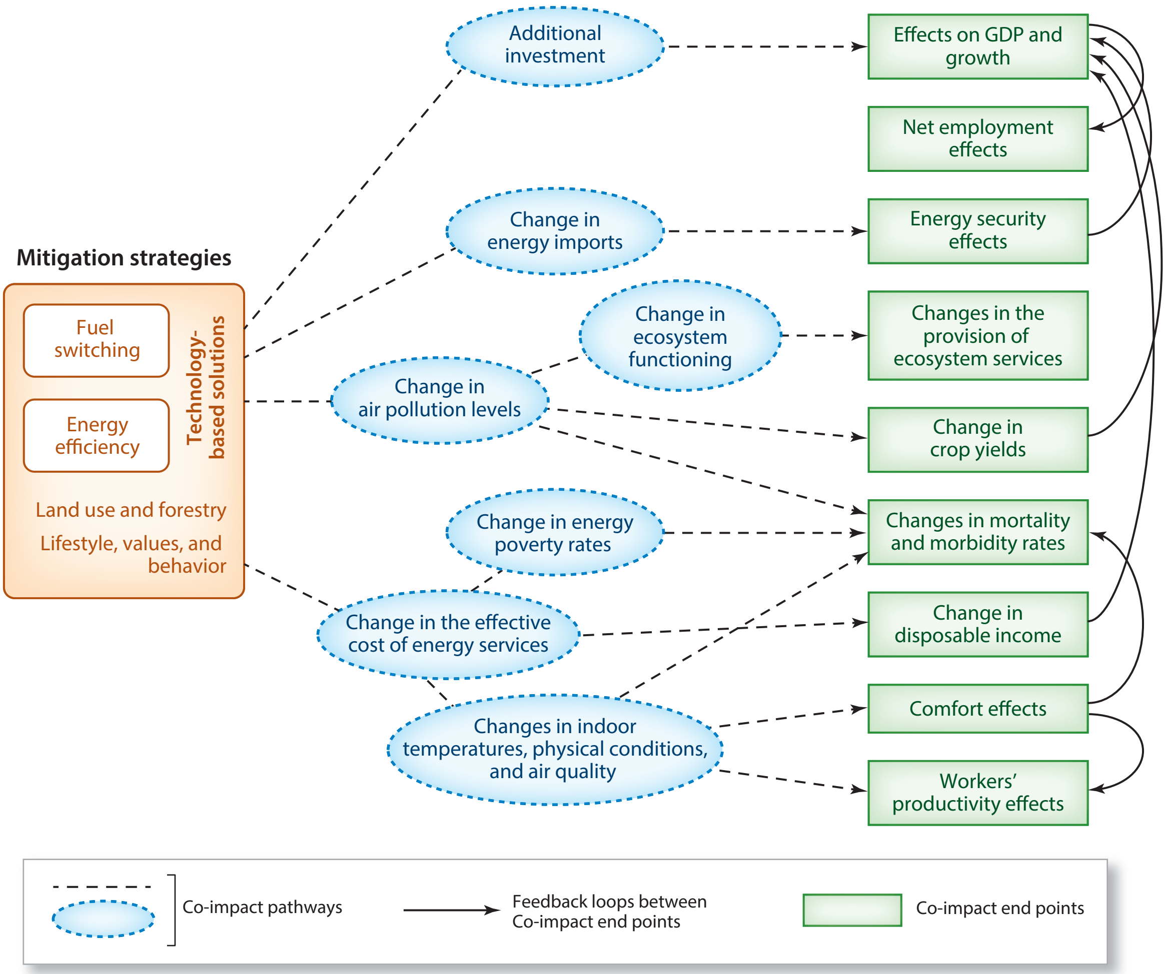

Figure 3

Conceptual map of the welfare effects of mitigation strategies and their interrelated nature.

Second, as some categories of co-benefits overlap, special care must be taken to avoid double counting, especially when monetary values are incorporated into decision-making frameworks, such as in a cost-benefit analysis. For example, improved air pollution resulting from investments in renewables or in energy efficiency affects household comfort, peoples' health, and workers' productivity (see **Table 2**). These three categories of co-benefits at least partly overlap. Careful analysis of welfare end points is therefore warranted to avoid double counting. Nevertheless, it is possible that in many cases the potential bias such double counting introduces to a co-impact assessment is smaller than the bias (*a*) left by failing to assess co-impacts that may not yet be fully understood or acknowledged or (*b*) for which quantification and valuation methodologies are not available (104). Therefore, it is worth considering whether the double-counting risk, if not possible to eliminate, is important enough to compromise an attempt at integrating the key co-impacts into the decision making.

Third, operating (for analytical purposes) with distinct individual co-benefit categories may hide complex dynamic relationships and feedback loops. For instance, renewables and energy efficiency reduce air pollution, which decreases health care costs versus a baseline and may release public resources that can be invested or spent on alternative uses and further enhance employment or gross domestic product levels. In this regard, it must be also pointed out that the overall positive and negative welfare effects of mitigation policies are seldom quantified or valued on a life cycle basis, with some environmental impacts left unaccounted for. This may be particularly relevant in the case of measures entailing the installation or upgrading of infrastructure (i.e., replacing industrial equipment or vehicles with more energy-efficient machinery, installation of renewable capacity, etc.) versus a business-as-usual scenario. For example, a recent assessment by Shih & Tseng (105) created a model to integrate the life cycle co-benefit assessment of sustainable energy policies but extended this only to air pollution and related health impacts.

Distributional effects are also important, especially when mitigation measures contribute to bridge the inequality gap. An example is public transport, which is more often used by the disadvantaged groups of society, such as the very young and elderly, females, and lower-income people, thus influencing the access of these population segments to economic opportunities (35). In India, climate policies can greatly reduce the morbidity/mortality impacts related to PM_{10} concentration levels, which are significantly higher in low-income areas, while imposing mitigation costs on the wealthier population (44). Therefore, in addition to a total welfare effect, it can also be important to consider the distributional effects of the policy/measure as decision criteria. In cases where there is a well-defined distributional outcome desired, this may enter the calculation of the overall welfare impact through weighing net benefits with equity factors based on differences on income distribution and well-being across socioeconomic groups (98).

In spite of the shortcomings described above, an important feature of valuation is that it provides a common measuring rod that, by expressing the value of changes in welfare in monetary units, allows adding and comparing market and nonmarket benefits with the costs associated with climate investments (106). However, for some of the categories identified (e.g., employment effects), limited examples of valuation techniques are as yet available, and for others (e.g., value of reduced mortality), some significant uncertainties remain. In those cases, similar to when monetization is controversial, reporting results in physical units is often advisable and can be combined with alternative assessment techniques, such as multicriteria analysis, described in Section 6.3.

6. INCORPORATING CO-IMPACTS INTO DECISION-SUPPORT FRAMEWORKS

In this section, we review three key methodological frameworks for incorporating these co-impacts into decision-making frameworks: social cost-benefit analysis, integrated assessment modeling, and multicriteria analysis.

6.1. Social Cost-Benefit Analysis

Cost-benefit analysis is a major appraisal technique for public investments and public policy, used in the fields of environmental policy, transportation planning, and health care (98). Its application as an assessment tool of regulatory and investment initiatives has been required by national and supranational institutions, e.g., the European Commission (129) and the US Office for Management and Budget (130).

Grounded in the theory of welfare economics, cost-benefit analysis provides a framework for the comparison of relevant policy options from an aggregated welfare perspective. In essence, cost-benefit analysis compares projects and policies based on the discounted sum of their costs and benefits to estimate the net present value of each option; these values are used as social profitability indicators when deciding on mutually exclusive projects. For the analysis to be complete and credible, identifying as many feasible, relevant alternatives (including a zero or do-nothing business-as-usual scenario) is required to ensure that a full range of options has been considered (99). However, cost-benefit analysis is not only important by its result (the aggregate net present value) but also by the fact that it forces one to enumerate and evaluate, as much as possible, all the consequences of the policies that are considered.

Two types of cost-benefit analysis can be conducted (99). Private or financial cost-benefit analysis measures the costs and benefits of a given project from the perspective of one economic agent (e.g., a household, a firm, the government), and therefore, only the costs and benefits accruing to that particular agent are taken into account. By contrast, social cost-benefit analysis aims at measuring the costs and benefits of a given project or policy from the perspective of society as a whole. In a social cost-benefit analysis, costs and benefits accruing to all affected parties should thus be taken into account—raising issues, as noted above, about not only the aggregate (net) costs and benefits but also about their distribution.

For the assessment of the co-impacts of climate policies, social cost-benefit analysis is the preferred appraisal tool because it measures costs and benefits as variations in human well-being (i.e., in utility), thus estimating the net contribution of each of the defined policy options to the aggregated welfare of the society. This is mostly a result of the methodological specificity that differentiates social cost-benefit analysis from financial cost-benefit analysis (98, 99, 129) and, in particular, a result of the quantification and monetization of nonmarket costs and benefits (like externalities) through a whole range of available economic valuation tools, as seen in **Table 2**. This is a key aspect of the social cost-benefit analysis methodology with regard to the quantification and valuation of climate co-impacts, which often occur as nonmarket costs and benefits.

6.2. Integrated Assessment Modeling

Important purveyors of mitigation policy analysis are integrated assessment models (IAMs), which evaluate the costs of different mitigation policies; see, e.g., chapter 3 of the IPCC's fourth assessment report (1), chapter 6 of the IPCC's fifth assessment report (5), or Sathaye & Shukla (4) for a review. Large-scale IAMs typically operate in a cost-effectiveness system, thereby not considering the primary benefit of climate mitigation. Direct costs of mitigation are estimated using a partial or general equilibrium analysis, depending on the model. But even in IAMs with general equilibrium models, macroeconomic feedbacks typically remain limited. For example, the employment effects of climate policies, implications for investment flows and trade balances, or interactions between climate policy and the fiscal setting are typically not captured (131). Environmental and health co-impacts are often estimated in a nonmonetary way. The MESSAGE model developed at the International Institute for Applied Systems Analysis (IIASA) computes local air pollution implications of particular measures (in atmospheric concentrations of particulates) via its GAINS submodel (132), but not the welfare implications of changes in pollution. The MESSAGE model has recently been applied to break new ground with more rigorous assessments and incorporation of multiple benefits, as described in (133, 134) and the *Global Energy Assessment* (135). However, even these extend analyses to the incorporation of only a selection of key co-impacts.

IAMs thus typically provide insights directly usable in multicriteria analysis (rather than cost-benefit analysis). Their strength is that they can potentially incorporate evaluations in both physical and monetary units. However, they are very complicated and require a sophisticated and complex model as well as a very large amount of data, excluding this method from instances when resources for decision support are limited.

6.3. Multicriteria Analysis

Multicriteria analysis is a technique that enables assessment of the impacts of a policy objective on multiple simultaneous outcomes (136, 137). Multicriteria analysis has at least three strengths that go beyond the contributions of social cost-benefit analysis that make it particularly suitable for climate-related decision making. First, it provides a framework to bring together quantitative and qualitative information, thereby allowing consideration of problems where quantitative or monetary information in the same currency is not available or cannot effectively be approximated through valuation techniques (137–139). Second, it allows the incorporation of stakeholders' preferences, which often vary on environmental issues, into decision making through a process of weighting objectives (116, 124). Third, it frames decision making in procedural terms by embedding decision making within a structured process of deliberation and discussion. This allows a more productive use of qualitative information, allows for weighting on the basis of stakeholder perspectives, and allows for iterative analysis, which promotes convergence toward better decision making over time (138). Although not exclusive to multicriteria analysis, the ability to productively use qualitative information alongside quantitative information and the emphasis on the process of arriving at the result through stakeholder deliberation distinguish it from other decision-support tools, such as social cost-benefit analysis.

Multicriteria analysis has a growing track record of use in environmental decision making (38), where the challenges of multiple objectives, choices, trade-offs, and valuation are particularly important (140–143). Brown & Corbera (140), for example, use multicriteria analysis to examine the broader development implications of forest carbon markets. A multicriteria analysis–based approach to climate mitigation policy has been proposed by Dubash et al. (40). The most ambitious effort to develop a multicriteria analysis framework to climate policy has been attempted by the United Nations Environment Programme (38). The framework is built around a hierarchical criteria tree containing generic criteria divided into a number of categories, which were described in Section 4.1.

It is important to understand both the strengths and the limits of multicriteria analysis approaches. The use of subjective values and weights is intrinsic to the method and is defended on the grounds that the approach makes these otherwise implicit weights explicit. To be credible, multicriteria analysis requires a supporting social process for discussion and decision making. As a result, the background work required can be substantial: (*a*) to clarify all assumptions, source information, and opinions and (*b*) to clearly communicate the results as well as the trail of argumentation and analysis leading to those results. Finally, for some approaches, the process rests on the robustness of the underlying functions that map the outcomes to utilities or values.

6.4. Summary and Research Needs

In practice, most of the literature on climate mitigation policies is framed within a cost-benefit analysis or IAM approach (as opposed to multicriteria analysis). However, a lack of data often leads to an analysis in which few co-impacts are taken into account (if at all) and in which the valuation of those co-impacts considered is based on financial rather than welfare analysis. There are, however, attempts at broadening the scope of these analyses; the Stern Review (144) is one example.

As shown above, a broad range of methods is available, most of them mature and well established, to assess individual co-impacts. However, these often require a very large research effort for the rigorous estimation of even one co-impact (such as estimating the employment impact of a renewables policy). Appraising each co-impact, as well as properly accounting for their interactions and incorporating these into decision-making frameworks, thus requires a huge effort even for a single policy/measure.

Two conclusions follow. First, further innovation is crucial to (*a*) identify and create streamlined methods and easy-to-use tool kits through which individual co-impacts in their local circumstances can be assessed without a major targeted research enterprise, and (*b*) to design simpler methodological frameworks to integrate these with direct impacts. Second, until such are available, alternative methods can be used for considering co-impacts in decision making. For instance, if a full integration is not possible owing to resource, time, or data constraints, the key co-impact could be selected for a rigorous quantified evaluation, using one of the methods proposed above, and the alternative climate policies/measures can be compared on the basis of this co-impact. In such cases, i.e., when integration into cost-benefit analysis is not needed, considering evaluations in physical units may be more advantageous than using monetary terms to avoid the controversies and biases introduced by translations into monetary units.

7. THE IMPORTANCE OF CO-IMPACTS IN SOCIAL COST-BENEFIT ANALYSIS

Although the main purpose of this review is to provide methodological guidance for assessing co-impacts and for their incorporation into decision making, one question undoubtedly emerges: How important are such efforts? The discussion above makes it clear that doing so is a challenging and complex task, but is it worth the effort? What difference does it make when the co-impacts are integrated into the analyses?

The quantitative and even qualitative literature is immature to provide an unambiguous answer to this question. We explore this question by identifying a few social cost-benefit analysis studies where an attempt was made to incorporate the co-impacts and where it is possible to compare the outcome with and without their integration. The selection of studies was primarily based on the availability of disaggregated results by categories of social benefits to assess in a quasi-quantitative fashion the relative weight of each category with final profitability indicators (net present values or benefit-cost ratios). Thus, rather than a comprehensive review, the studies collected provide an illustration of the importance of co-impacts in social cost-benefit analysis studies.[4]

Table 3 presents these studies and attempts to quantify the importance of co-impacts as compared to direct or total impacts on welfare through the selected indicators. Note that all the studies compiled were conducted at national and subnational scales, which draw the attention to the fact that co-benefits are significantly more context, location, and case specific than direct climate or energy benefits, making it much more challenging to draw generic conclusions about co-benefits. At the same time, the study findings are not just strictly representative of the cases and places reported but also show some consistent trends that are meaningful for this review.

Even though the value of climate and other co-benefits largely depends on the assumptions taken, one key conclusion to be drawn from the cases collected is that co-benefits do play significant roles and uniformly change the outcome of the cost-benefit analysis, as shown by the comparison of different benefit categories (see the column entitled "Co-benefit categories in order of relevance" in **Table 3**). Even if direct benefits often represent the largest share of total benefits, co-benefits can amount to as much as 50% to 350% of direct energy benefits from technology-based investments in energy efficiency and renewables (cases 1 through 5). This initial scan also suggests that health-related benefits often dominate in terms of the importance of the different categories of co-benefits, as had been previously suggested by Pearce et al. (98) and Arrow et al. (145).

Study results of efforts to prevent deforestation and forest degradation, as in the investments promoted by global initiatives like Reducing Emissions from Deforestation and Forest Degradation (known as REDD+), indicate that the value of carbon storage in ecosystems may not always be the main benefit of mitigation measures unless a high value of carbon is chosen (see cases 6 and 7

[4]Most of the cases reviewed, with some exceptions like the one from New Zealand (111), are unsurprisingly prospective or ex ante studies because social cost-benefit analysis is a tool primarily used to assess the social desirability of different options before a decision is taken.

in **Table 3**). In fact, the selected per unit values of the carbon captured and stored in ecosystems, as well as the value of other benefit categories (e.g., storm protection in the case of Thai mangroves, watershed protection in the case of Ethiopian cloud forests), are key parameters that determine the relevance of climate benefits in total economic value estimates. The importance of ecosystem nonmarket benefits, many of which can be referred to as co-impacts, has been highlighted by a parallel strand of the economic valuation literature that advocates for valuation of ecosystem services and the estimation of ecosystems' total economic value for properly understanding the overall contribution of ecosystems to human welfare (146, 147).

This brief review of case studies suggests that co-benefits are indeed important as they have the potential to significantly change the outcome of economic assessments of climate interventions. Its inclusion demonstrates that measures or policies with a more or less strictly defined climate goal have a diversity of positive welfare effects on both present and future generations, which often more than justify implementation costs as shown by the positive net present values and the larger-than-one benefit-cost ratios reported in **Table 3**.

8. SUMMARY AND CONCLUSIONS

Co-benefits have become a key area of climate change and energy discourses. In an ideal case, every time a decision is made about a climate- or energy-related investment or policy, it should be done with consideration of its full range of costs and benefits. Nevertheless, this practically never happens, partially because methodologies that incorporate co-impacts into traditional decision-making frameworks such as cost-benefit analysis are either lacking or are too immature.

The goal of this review was to provide initial methodological guidance for the incorporation of co-benefits (co-impacts) into decision-making frameworks. More concretely, the article supplies a methodological walking stick for the definition, taxonomization, identification, and quantification/valuation of co-impacts and their incorporation into three key decision-support frameworks using a broad synthesis of the available co-benefit literature. After defining the related terminologies and concepts used, we suggested the broader use of the term co-impacts in place of many others used in the literature. Because policies or measures are typically not introduced for the single purpose that results in the co-benefits, the importance of a multiple-objective–multiple-impact framework for the analysis of co-impacts is emphasized.

Then, after a review of the different categories of co-impacts, we argued that it is not possible to give a distinct taxonomy of these because of their interdependency. Instead, a methodological framework is suggested for identifying and organizing co-impacts for particular cases, along with a range of categories—not fully independent from each other—that can be considered when identifying co-impacts for investments or policies, providing the analysis includes a thorough understanding of their causalities and interdependencies. The application of such methods can help avoid double counting or avoid missing important co-benefits or adverse side effects. We provided a thorough review of various indicators used for the quantification of each of the main co-impact categories identified, both in monetary and physical units, and reviewed the available methodologies for their assessment.

However, even if co-benefits and adverse side effects are identified, taxonomized, and potentially quantified, their incorporation into decision-support frameworks still poses a challenge. We reviewed three key such frameworks: multicriteria and social cost-benefit analyses as well as integrated assessment modeling.

These methodological reviews showed that a proper assessment of co-benefits and adverse side effects is a complex and potentially resource-intensive task. Few studies exist in the literature that thoroughly considered the full range of costs and benefits, including co-benefits and adverse side effects; that considered their interactions and feedbacks; and that evaluated their full net impact. Therefore, it is important to understand whether these efforts are worthwhile. The review of selected studies where such work has been attempted has shown that the assessment of co-impacts is indeed extremely important and that their incorporation may substantially change the outcomes of cost-benefit analyses. In the reviewed cases, the co-impacts amounted to as much as 50–350% of the direct or total benefits. Therefore, if properly considered, they can indeed become game changing. The review of these case studies also suggested that health-related co-benefits may be among the largest, most important category of co-benefits, although these require substantial further work.

An important conclusion of the review is that co-impacts are substantially more context and location specific than direct impacts often are. Although the direct costs and benefits of a mitigation policy or investment can be more or less universally estimated, the indirect impacts can differ even in the same locality, for instance, by beneficiary; this needs to be recognized by methods and tool kits designed for streamlined incorporation of co-impacts into decisions.

The review points to the immense need for comprehensive studies that incorporate all multiple impacts into the policy appraisal and on the development of easier-to-use streamlined methodological packages and decision-making tool kits that will substantially simplify and automate the evaluation and incorporation of co-impacts into decision support. Although the theoretical underpinnings are all available and well established, there is a severe lack of practical, targeted, simplified methods and tool kits that enable broad everyday consideration of co-impacts in climate- and energy-related decision making or, more precisely, that aid decision making in a complex, multiple-purpose framework, executed with limited resources. However, until such frameworks are available, or even if the analysis of the full range of impacts is not possible, assessing a single or selected co-benefit(s) or side effect(s) may also be carried out by partially applying the methods shown above to assist decision making.

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