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Measuring multiple impacts of low-carbon energy options in a green economy context

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Abstract

The economic assessment of low-carbon energy options is the primary step towards the design of policy portfolios to foster the green energy economy. However, today these assessments often fall short of including important determinants of the overall cost-benefit balance of such options by not including indirect costs and benefits, even though these can be game-changing. This is often due to the lack of adequate methodologies.

The purpose of this paper is to provide a comprehensive account of the key methodological challenges to the assessment of the multiple impacts of energy options, and an initial menu of potential solutions to address these challenges.

The paper first provides evidence for the importance of the multiple impacts of energy actions in the assessment of low-carbon options.

The paper identifies a few key challenges to the evaluation of the co-impacts of low-carbon options and demonstrates that these are more complex for co-impacts than for the direct ones. Such challenges include several layers of additionality, high-context dependency, and accounting for distributional effects.

The paper continues by identifying the key challenges to the aggregation of multiple impacts including the risks of overcounting while taking into account the multitude of interactions among the various co-impacts. The paper proposes an analytical framework that can help address these and frame a systematic assessment of the multiple impacts.

Keywords: Multiple benefits, co-benefits, adverse side-effects, Energy efficiency, green economy, Multiple benefit quantification methodology, Impact pathway, Quantification methods, cost-benefit analysis

1 Introduction. Rationale and goals

1.1 The importance of the multiple benefits discourse in the context of the green economy

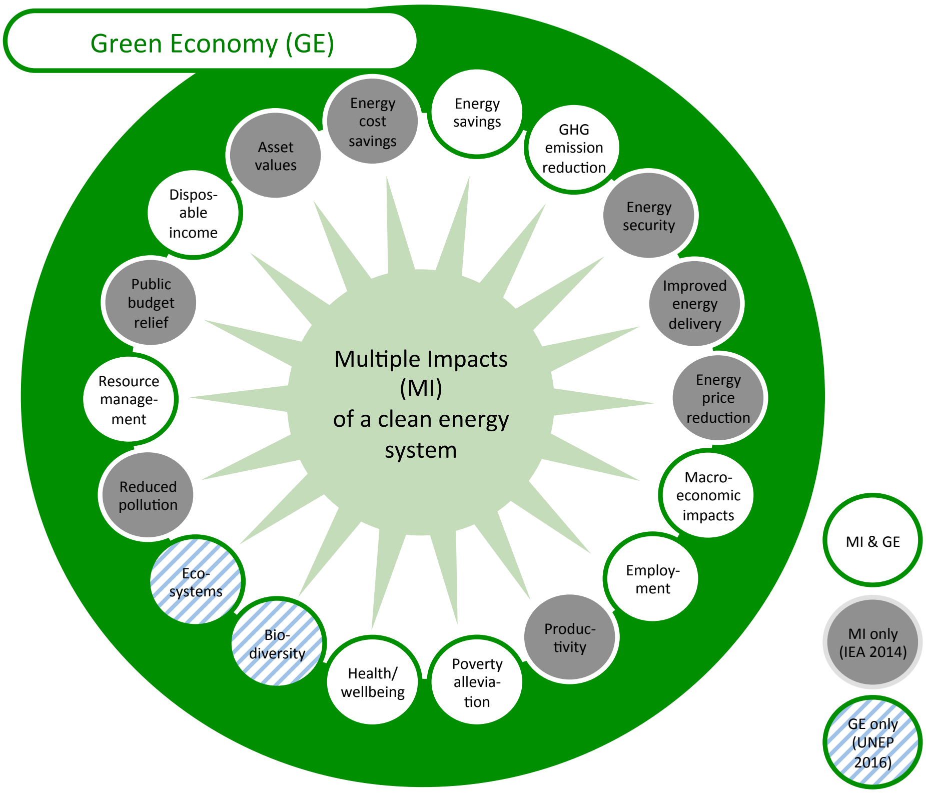
Improved energy efficiency and renewable energies have been integral parts of 'Green Economy' concepts from the very beginning and have become particularly prominent in light of the financial crisis [1][2][3]. UNEP founded the Green Economy Initiative in 2008 with the target of achieving an economy which is not only green, but one that results in "improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities"[4]. Put simply, a green economy can be thought of as "low carbon, resource efficient and socially inclusive" [4].

At the same time, in the energy and climate change research and policy fields, the concept of "multiple benefits" (also termed "co-benefits", "multiple impacts", "non-energy benefits", etc.) has evolved as a field of analysis showing that the impacts of low-carbon energy transformations go hand-in-hand with many other societal and economic objectives. Here we use the term multiple impacts (MI) to denote all benefits and costs related to the implementation of low-carbon energy measures which are not direct private benefits or costs involving a financial transaction and accruing to those participating in this transaction.

With the work of the IEA [5],[6]the discourse of multiple benefits has been particularly prominent in the context of energy efficiency but has also been prominent in relation to renewable energy [7]). The idea has also been applied in a broader energy and climate change policy context (e.g.[8], [9], [10][11]).The multiple benefits of increased use of energy efficiency and, depending on circumstances, renewable energy may include avoided or deferred transmission and distribution investments for customer-sited renewables, energy security, job creation and development opportunities, poverty reduction, an increase in disposable income, economic output and total wages, and a contribution to meeting air quality standards and reduction in local environmental damages[12][13]. Renewable energy can also contribute to providing universal access to energy, particularly to those who still have no connection to the electricity grid, e.g., through solar PV, micro-hydro, and biogas installations, which in turn contributes to goals related to economic development, livelihoods, education, rural development and gender equality for people who currently have no access to electricity and rely on traditional fuels for their energy needs[14][15][16].

A successful transition of the energy system towards a low-carbon one comes with an array of such effects and can contribute directly to a Green Economy. For instance, improved energy efficiency translates into several indirect benefits contributing to the goals of a green economy[17]: energy savings reduce scarcities in energy resources and thus reduce social inequities between countries and generations in regards to these resources. Energy savings reduce energy costs, thereby improving human well-being directly and in many cases can contribute to improved competitiveness of businesses; they reduce greenhouse gas and other emissions harmful to humans and the environment, and they reduce the risks associated with energy supply such as energy import dependency. However, these impacts need to be positive in a balance of net effects, also taking into account the incremental costs of increasing energy efficiency, including embedded energy consumption and emissions in the production of more energy-efficient goods and services. The same is true for the need to evaluate net employment effects due to investment in low-carbon options instead of traditional energy supply, for net income effects, and net impacts on resource consumption as savings in the use phase of high-efficiency products may be partly offset by additional resource use for their production. In addition, incremental costs and benefits of energy efficiency and renewable energy may not always accrue to the same persons, as in the example of rented apartments or offices, so distribution may matter too. These simple examples already highlight two issues: first, evaluating multiple impacts of low-carbon energy options is of central importance in order to assess how much a specific energy system option is contributing to the objectives of a green economy and second, it is far more complex to evaluate all the multiple impacts than just the direct benefits, such as direct energy cost and emissions reductions.

Figure 1: Overlaps between two concepts – Green Economy (GE) and Multiple Impacts (MI) of Energy Efficiency. Comparison of the benefits mentioned in the UNEP report on Green Economy [18] and the IEA report on Multiple Benefits of Energy Efficiency [5].



Source: Own depiction based on the "multiple benefits flower"(IEA 2014, 20).

Note: Impacts in green/dark line small circles depict coverage by Green Economy targets [18], small circles multiple benefits of a low-carbon energy system. White spheres are not covered within the IEA [5]concept.

Arguments put forward in the Green Economy [18] discourse overlap largely with those from the Multiple Benefits of Energy Efficiency discourse. Figure 1 presents the benefits from low-carbon energy systems based on the logic of the IEA 2014 report, but includes several additional or differently framed benefits (e.g. pollution reduction or productivity gains). Similarly, additional Green Economy arguments may well count as Multiple Benefits. Most of the impacts mentioned by the IEA[5] can be considered to contribute to a Green Economy, even if they are not explicitly mentioned by UNEP. The levels where individual benefits occur are, however, diverse (e.g. investor/end-user, societal, organisational, country or global) and can be linked (e.g. disposable income and poverty alleviation). The impacts in Figure 1 are not prioritised or organised; there can be overlaps among them.

Table 1 shows in more detail the synergies between the three main Green Economy Elements and specific Multiple Benefits of energy efficiency improvements.

Table 1: Elements of the Green Economy as defined by UNEP [4]and the overlapping multiple impacts of energy efficiency improvements based on the categorisation used by IEA[5]

Elements of a Green Economy	Multiple Impacts of energy efficiency (EE), renewable energy (RE) and public transport improvements
Improved human well-being	Increased disposable income resulting from decreased energy expenditure Employment impacts, including the positive direct impact of EE & RE investments and the positive indirect impact of increased disposable income, as well as decreased employment in the fossil energy sector Industrial productivity increase from energy efficient equipment and increased air quality and thermal and visual comfort of workers, reduced cost of operation and maintenance, energy-related cost reduction and mitigation of financial risks from energy savings in energy-intensive industries, lower cost of environmental compliance Macroeconomic impacts including economic output, prices, and trade balance effects resulting from investment and energy demand changes Increased asset values through general improvement of infrastructure and capitalisation of energy savings Health and well-being, including reduction of respiratory and pulmonary disease, lower winter excess mortality and morbidity, increased thermal comfort, improved mental health due to reduced stress associated with bill payments and, improved nutrition Improved energy delivery through more reliable energy service and new generation, avoided operating and capacity costs for energy generation, transmission and distribution, smaller reserve requirements Increased energy security at national level, in particular, increased sovereignty and resilience
Improved social equity	Positive public budget impacts from energy cost savings, reduced need for energy subsidies and unemployment and social welfare related subsidies, reduced health care costs due to reduced exposure to air pollution, improved housing quality, and increased general physical activity, and increased tax revenues via positive employment impacts, as well as some employment impacts, as mentioned above Poverty alleviation through reduced energy bills, increased disposable income, and increased employment Reduced energy prices due to reduced energy demand, as well as reduced cost of energy services resulting in increased welfare and decreased fuel poverty
Reduced environmental risks and ecological scarcities	Lower GHG emissions resulting in decreased climate change impacts Improved resource management including energy, water and air Reduced exposure of ecosystems to acidification, eutrophication and ground-level ozone due to reduced air pollution Reduced corrosion of the infrastructure

However, the co-impacts[1] of low-carbon energy investments may not always be benefits – as Urge-Vorsatz et al.[19]review the various types of impacts and terminologies related to the indirect impacts of green energy investments. For example, transaction costs related to low-carbon energy investments may be significant [20]. Some of the transaction costs, such as costs of negotiation or monitoring and verification, will be wholly or partly monetized and therefore included in direct costs, but other transaction costs such as search and information

[1] In the literature, there is a broad array of terms used for these: co-benefits, multiple benefits, ancillary benefits, indirect costs and benefits, external costs, adverse side-effects, risks, etc. Urge-Vorsatz et al. [19] provide a comprehensive account of these terms. The same paper argues for using "multiple impacts" due to various reasons, including that it often cannot, or should not, be predetermined whether an impact is positive or negative. We stick to this terminology in this paper. When the impacts beyond a specific main benefit or objective are discussed, we use the "co-impact" term; but when the co-existing various multiple impacts are discussed in a multiple object framework, we mostly stick with the "multiple impact" term.

costs may not be monetized and can, therefore, be considered as co- impacts. Some types of policies, e.g. informative policy instruments, result in lowered transaction costs

1.2 Limited use of multiple impacts in the assessment of energy system options

The multiple aspects tackled in the green economy discourse can also be found in national and supra-national energy policy. Multiple policy goals, expanding traditional goals of reduced non-renewable energy demand or lowered greenhouse gas (GHG) emissions, have been formulated. According to the policy framework of the European Union, economic opportunities (growth and job creation and cost savings to consumers), as well as reduced energy import dependence, are important objectives of European policies[21]. The Energy Efficiency Directive [22] explicitly states the policy targets not only of climate change mitigation, but also innovation, competitiveness, economic growth, high-quality jobs and resource efficiency.

In addition, several national energy policies have recognised the causal links between cold and damp housing and poor health and the positive impact of energy efficiency policy to overcome the situation of poor human health (e.g. Warm Up New Zealand, Warm Front Scheme in the United Kingdom). Beyond these impacts already partly anticipated by policy, also unanticipated, but desired impacts might occur. A concrete example of the benefits of linking energy and climate policy to other policy areas is the link to air quality and health policy. For example, a study by Amann et al. [23] found that if the EU implements the climate policy goal of reducing greenhouse gas emissions by 40%, as well as reaching a 27% share of renewable energy and a 30% improvement in energy efficiency, the goals of the Clean Air Policy Package can be achieved at a cost that is €2.2 billion less per year than without achievement of the mentioned climate policy goals.

Summing up, a comprehensive assessment needs to not only consider the direct costs and benefits of different energy technology choices but also cover the multiple (anticipated and unanticipated) impacts of energy policies. However, although some examples of studies which cover a wide array of multiple impacts exist, such as in this journal (e.g. Schweitzer and Tonn,[24]),this has not yet become commonplace in the assessment of energy system options and policies, especially not when quantitative assessments are conducted (see Ryan & Campbell [6] and Urge-Vorsatz et al. [19]). Cost-benefit or cost-effectiveness analysis typically include only direct costs and benefits. Partially the reason is the lack of methodologies that can consistently and comprehensively account for all co-impacts, and integrate these into quantitative decision-making frameworks.

At the same time, there are very few studies that attempt to systematically address the relevant associated benefits/impacts of transitions to low-carbon economies spanning across multiple impact areas and thus disciplines [25][26][27]. Also in this journal most studies focus on synergies and trade-offs of climate change mitigation and green energy options in relation to only one policy area, e.g. air pollution, social welfare, resource efficiency, energy security, macroeconomic performance (e.g. Dong et al. [28],Takeshita[29]and Zhang et al. on air pollution[30], Xi et al. [31]on environmental benefits, Dai et al. [32]on economic benefits and Li & Lin, [33] on productivity benefits). These studies are generally case studies of a single country or a single impact and do not address methodological issues related to the difficulties of systematically assessing or integrating MIs.

Even the few studies which estimate values for several MIs (e.g. Schweitzer and Tonn,[24]) do not address challenges related to integrating independently estimated MI values to arrive at total value. This remains a major methodological knowledge gap. EPA [13]) proposes steps for assessing the multiple benefits of low-carbon energy and proposes methods for assessing individual benefits but does not make any suggestion on how to aggregate individually assessed MIs. Similarly, IEA[5]discusses methodologies which can be used to estimate individual benefits but does not propose a methodology for arriving at a total value, avoiding the issue altogether. In the existing literature, there is little recognition of the complexity of integrating individually estimated benefits to arrive at a value for total benefits.

The development of a methodological approach to estimate the indirect impacts/benefits of low-carbon energy options and to integrate it into decision-making frameworks could also enrich green economy policy evaluation methods.

1.3 Goals and scope of the paper

Information on the magnitude of multiple impacts of energy system options is extremely important for a well-informed design of policies towards a green economy. However, as has been shown, presently these impacts typically are not considered in quantitative decision-making frameworks, in part because of the lack of methods for their consistent, comprehensive evaluation and integration[19].

Thus, the purpose of this paper is to contribute to the development of a methodological toolbox for evaluating low-carbon energy system actions and policies in a more holistic perspective: how to integrate the assessment of multiple impacts into traditional cost-benefit analysis in a methodologically and theoretically consistent manner.

The structure of the paper is slightly different from the standard structure in this journal, because it uses an inductive approach rather than a deductive one. After a description of the methods and scope, the paper first highlights the economic and social importance of MIs[2] by citing existing evaluations that typically find MI values being at least as big as direct impacts. Then, the paper provides an overview of the theories and methods used to evaluate these multiple impacts. In the subsequent sections, the paper contributes to new theory by systematically identifying the key challenges analysts face when they aim at comprehensively accounting for all indirect costs and benefits of a low-carbon energy action/policy: First, challenges to the evaluation of individual co-impacts, and second, those to a comprehensive integration of these co-impacts. The paper finally proposes a set of solutions to these challenges, including a new methodological framework for systematically identifying, evaluating and integrating the multiple impacts of low-carbon energy actions/policies.

In terms of scope, since the paper's aim is to contribute to the development of new methodological approaches for low-carbon energy options, it aims at comprehensiveness in a methodological sense, and not in its topical coverage. Therefore, it uses low-carbon options as illustrations of the relevant concepts, and does not aim at a comprehensive coverage of the full spectrum of low-carbon energy options. In terms of examples, it focuses on two key domains of low-carbon energy options: improved energy efficiency and increased penetration

[2] Multiple impacts take place any time there is a change in the energy system. Therefore, the discussion pertains to both technical changes or the policies that result in these technological changes. Thus, the paper refers to both low carbon energy options and policies when the multiple impacts are discussed, throughout the paper.

of renewable energy generation, but also brings examples from other areas such as lower carbon transport.

The contribution of this paper to knowledge is manifold – but each contributes to methodological advances. First, by providing the first systematic account of the challenges to assessing multiple impacts, the paper provides a framework for future rigorous MI evaluations on a routine basis. There have been several studies carried out in the past that have overlooked some of these pitfalls with the results giving rise to criticism[3]. Therefore, a structured and comprehensive guide will enable a more routine preparation of authoritative MI assessments. Second, among these methodological challenges and pitfalls, some are documented and described for the first time in this paper, including a newly introduced granular approach to additionality. Finally, the paper proposes a novel analytical framework that can assist in addressing several of the identified challenges for which no systematic solution existed before. The paper also suggests key areas for further research that are necessary to develop the methodological tools to make the evaluation of multiple impacts and their integration into traditional decision-making frameworks a simpler, cheaper, faster, more routine task.

2 Methods

Because this paper aims at contributing to the development of methodological frameworks, a deductive research approach is not appropriate. Therefore the paper uses an inductive approach – i.e. starts with observations of previously researched phenomena to identify new trends, and theories (here methods) are formulated as a result of observations [34].The previously researched knowledge basis used for the observation of new trends presented in the paper is the extensive previous research on multiple impacts by the authors of this paper, as well as from the multi-partner European research project "COMBI[4]" quantifying multiple benefits in an in-depth, rigorous manner. More precisely, the findings presented in this paper were "by-products" of research aiming at the quantification of co-benefits in several research projects – the results of the methodological struggles these efforts have faced. The purpose of these projects was to quantify the co-benefits related to various energy efficiency measures (see, e.g. Suerkemper et al [35], Suerkemper et al [36], Urge-Vorsatz et al [37], Tirado Herrero et al [27]).During these research projects more and more challenges and pitfalls were gradually recognised, often at the cost of making mistakes in initial project phases.Finding solutions to these challenges have sometimes taken significant efforts by the experts, and much discussion among the researchers.

As identifying the challenges and their solutions to these problems was not the explicit purpose of any of these projects, these remained unpublished and unaddressed, but it became clear that there is a gap in knowledge regarding a systematic methodological guide that helps in avoiding these initial mistakes or at least streamlines the process and offers the solutions in an easily accessible format. This paper fills this gap by synthesizing the collective experience and knowledge of the authors that was gained as "by-products" in these research pro-

[3] For example, Edenhofer et al. [12] caution that claims that renewable energy investments create jobs may not always hold true and note that renewable energy subsidies "must be compared with other policy instruments that push the economy towards its capacity frontier. These short-term welfare comparisons of different policy instruments have not been carried out in reliable studies."

[4]COMBI – Calculating and Operationalizing the Multiple Benefits of Energy Efficiency in Europe. The project has received funding from the European Commission under Grant Agreement No. 649724 (http://combi-project.eu).

jects; i.e. documenting the inductive advance in knowledge that took place during these research efforts.

The paper's approach is to systematically account for these challenges and pitfalls, and identify the potential solutions or constructing new analytical frameworks. Some of the solutions have been proposed based on literature from similar areas of enquiry or, if such did not exist, drawing parallels and gathering ideas from other disciplines or areas of research (for instance, drawing from methods in climate finance, such as related to additionality).Finally, as some challenges have not been found to be sufficiently rigorously addressed in earlier studies, the paper proposes a new framework to overcome these. The framework has been developed during the EU project "COMBI", through a collective gathering of the diverse experiences of the authors on related research projects, and through a joint development and testing exercise in which related approaches were examined from other disciplines and problem areas for their transferability.

The progress towards a Green Economy has so far been measured mostly with methodological frameworks traditionally supporting complex decisions top-down, such as welfare analysis, integrated assessment, multi-criteria analysis and indicator-based assessment (see e.g. for ex-post assessments USDoC[38], OECD[39], UNEP[40],World Bank[41]. Instead of competing with these, the proposed framework complements these approaches by enabling a more systematic incorporation of multiple impacts into bottom-up ex-ante assessments including interdependencies of impacts, thus better capturing the dynamics and complexities of policies and low-carbon options. This has the additional potential to better identify inevitable policy trade-offs.

It would be ideal to present a methodological framework that has been thoroughly tested. However, for evaluating multiple impacts, each quantification and integration exercise is a significant, often multi-year, multi-person effort, so this was not possible within the context of this paper. Instead, the paper concludes with the proposal for the framework and presents the initial experiences of the COMBI project in implementing (and developing) the framework, and leaves the testing and more experienced description, as well as the full account of its limitations, for future papers.

3 Theory

3.1 Importance of the multiple impacts of low-carbon energy technology options in the assessment of energy options

Empirical estimates indicate that the size of MIs of low-carbon energy options is significant. For energy efficiency improvements, the size of MIs can be commensurate with or larger than the direct benefit of lower energy costs. According to an analysis of the data by ICF Consulting, of the 52 monetized case studies, in 63%of the cases, the value of the MIs were equal to or greater than the value of energy savings. Among 30%of these case studies the MIs valued three times more than the energy savings, and in about 25%of the cases, the MIs were more than four times the energy savings [42],[43]. A review of selected social cost-benefit analysis case studies attempting a full coverage of co-benefits in the buildings and industry sectors found that co-benefits and non-climate benefits were between 53 to 350%of direct benefits in NPV calculations [19] and has been illustrated by some studies in Table 2. In the industrial sector, MIs may be 2.5 times the value of energy savings [44], [45].

Table 2: Results from a handful of studies are summarised

Study (reference)	Energy efficiency action	Ratio MIs/direct benefits	MIs covered
Buildings			
Joyce et al. [46]	Energy efficient refurbishment of buildings in the EU	1 in the *low EE* scenario to 1.33 in the *high EE* scenario	Health benefits, reduced outlay on subsidies, and reduced air pollution
Clinch and Healy [48]	Retrofitting energy-efficiency technologies and heating upgrades in the Irish residential building stock	1.7	Health benefits (mortality and morbidity), comfort benefits, and emissions reductions (CO_2, SO_2, NO_X, PM_{10})
Chapman et al. [26]	Retrofitting residential buildings with insulation in low-income communities in New Zealand	3.2	Reduced hospital admissions, Reduced days off school, Reduced days off work, and CO_2savings
Levy et al.[49]	Retrofitting across residential buildings with insulation in the United States (US)	0.22	Health benefits (mortality, asthma attacks, and restricted activity days)
Grimes et al. [50]	Insulation and installation of clean heating in New Zealand	74	Health benefits (prescriptions, hospitalisations and benefits of reduced mortality)
Aunan et al. [51]	Mix of household energy efficiency measures including individual, minimum standards for insulation of new buildings, energy efficiency labelling of household appliances, energy savings awareness raising and education; Energy Saving Credit Programme; and prioritising energy efficiency in state-financed R&D programmes	2.43	Health, materials, vegetation, and climate benefits
Scheer and Motherway,[53]	Energy efficiency improvements in the residential and small-business sectors	1.23 (in 2030)	CO_2 saved Other emissions (NOx, SOx, VOCs and particulate matter) saved
Schweitzer & Tonn, [54]	Weatherization assistance program for low-income residential buildings in the US	1.05	Ratepayer benefits Household benefits Societal benefits
Industry			
Finman &Laitner,[42]	Uptake of energy efficient technologies in 52 manufacturing case studies including food, building, steel, paper, chemical, and textiles industry	1.21	Reduction in waste/materials, water used, air pollutants (SO_2, NO_X and CO_2, CO, VOCs, and hydrocarbons), dust emissions, equipment wear and tear, and labour costs
Lung et al. [56]	Industrial energy efficiency measures from 81 projects that represented a variety of efficiency improvements including equipment replacement, technological upgrades	0.45	Ancillary savings and production benefits fall into five principal categories: Operations and Maintenance (O&M), Production, Work Envi-

	and reconfiguration of existing equipment		ronment, Environmental, and Other
Lilly &Pearson, [44]	Five projects were selected for industrial energy efficiency programs ranging from cement mill to cold storage in the US representing a variety of efficiency measures	0.31	Enhanced production and capacity utilisation, Reduced resource use and pollution, Lower operation and maintenance (O&M) costs
Transport			
Macmillan et al.,[57]	Integrated simulation model and cost-benefit analysis of future bicycling policies in Auckland, New Zealand.	0.7-3.9 depending on scenario	Health effects (reduced air pollution, increased physical activity and road traffic accidents)
Renewable Energy			
Fisher et al [58]	Renewable energy and energy efficiency	No numerical figure provided, “co-benefit exceeds the all-in cost of coal-fired generation in almost all circumstances” and “externality cost ranges from \$36 to \$43 per MWh hour today, rising to \$45 to \$51 per MWh by 2020,these costs are comparable to the direct costs of generation (i.e. fuel, O&M, and capital recovery). “	Air quality, health, water
Bergman and Hanley [59]	Renewable off-shore wind farms in Scotland	0.53 (1-mile off-shore turbine) to 0.6 (20-mileoff-shore turbine) of direct electricity output benefits	Displaced pollution, with 5 sub-categories: 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_2emissions.
GarcÍa-Frapolli et[60]	Improved biomass cookstoves in Mexico	0.83 of direct fuel wood saving benefits	Health impacts Environmental impacts (forest reserve preservation and GHG reduction) Job creation and income generation

3.2 Methodologies applied to the assessment of the multiple impacts of low-carbon energy options

Different types of MIs require different assessment approaches. An assessment method for valuing externalities (and especially more localised externalities such as the impact of pollution on health, ecosystems, crops, the built environment and resource depletion) is cost-benefit analysis. Macroeconomic models such as Input-Output analysis, partial equilibrium and Computable General Equilibrium (CGE) models or econometric models are generally used to assess macroeconomic impacts. Integrated models can be used to assess the environmental impact of energy efficiency or renewable energy policies. Multi-criteria analysis is very versatile and can be used to assess virtually any impact or combination of impacts. As not all methods are suited to assess all types of MIs, and different methods have different limitations, results from different methodologies can be presented side by side to complement each other, as further described in the below table. Given that different units are used to report results for each method, MI assessment outcomes are better compared across low-carbon options implementation scenarios (e.g. moderate vs. deep retrofits) than across assessment methods (e.g. Computable General Equilibrium vs. social cost-benefit analysis) especially when the aim is to inform decision-making processes.

Table 3: Summary of the most common methodologies used to assess multiple impacts in physical and monetary terms

Impact	Method
Employment impacts	Computable General Equilibrium models Input-Output models Macro-econometric models Partial equilibrium analysis CBA - Friction cost approach
Industrial productivity	Qualitative approaches (case studies, focus groups, systemic interviews and surveys)
Macroeconomic impacts including economic output, prices, and trade balance effects	Computable General Equilibrium models Input-Output models Macroeconometric models Partial equilibrium analysis
Disposable income	Computable General Equilibrium models CBA of energy efficiency investments – savings in energy expenditure vs. incremental investment
Asset values	Market prices/adjusted market prices (shadow prices) CBA - Damage cost avoided/expected damage function approach for impacts on physical structures
Health and well-being	Health Impact Assessment and regression analysis for physical impact estimation Various valuation methods: Revealed preference methods, e.g. compensating wage/wage-risk studies Stated preference methods e.g. contingent valuation, conjoint techniques Cost of illness approach/Cost of treatment for mortality and morbidity related benefits Human capital approach: Days off work/lost wages or Lost output/lost productivity for mortality and morbidity related benefits Averting behaviour method Defensive expenditure method
Energy delivery	Cost-effectiveness analysis
Energy security	Estimation of the macroeconomic external costs of energy imports Stated preferences (contingent valuation)
Public budget impacts	Energy audit for public sector energy cost reduction Fiscal multipliers for changes in public revenue Computable General Equilibrium models Input-Output models Macroeconometric models
Poverty alleviation	Input-Output models Macroeconometric models Computable General Equilibrium models CBA of energy efficiency investments – savings in energy expenditure vs. incremental investment
Energy prices	Computable General Equilibrium models Macroeconometric models Partial equilibrium analysis
Energy savings	Energy audit Bottom-up energy models Integrated Assessment Models
GHG emissions	Energy audit Integrated Assessment Models Bottom-up energy models Life Cycle Assessment
Resources	Market prices/adjusted market prices (shadow prices) for resources such as water, timber, land) Integrated Assessment Models Environmental Impact Assessment Life Cycle Assessment

Air pollution	Various valuation methods: Revealed preference methods such as the hedonic housing price Stated preference methods e.g. contingent valuation Various methods to assess health benefits (see above) Various methods to assess benefits related to asset values (see above) Integrated Assessment Models Environmental Impact Assessment Life Cycle Assessment
Ecosystems and biodiversity	Various valuation methods: Production function approach Revealed preference methods such as travel cost method Stated preference methods, e.g. contingent valuation Damage cost avoided/expected damage function approach Restoration/replacement cost Integrated Assessment Models Environmental Impact Assessment

Source: Based on Barbier[61] ,Bateman , Mace, Fezzi, Atkinson, & Turner[62], Boardman et al[63], IEA[5], Pearce, Atkinson, & Mourato[64], Rothman[65] , Sculpher [66], Ürge-Vorsatz et al [19]

4 Findings

4.1 Methodological challenges to the assessment of multiple impacts

This section reviews a number of methodological challenges that have been found, during the work of the authors on the assessment of multiple impacts using the methods described above, to have a major influence on the findings, and where longer scientific discussions with peers have helped in finding the solutions. While there may be many other issues, these represent challenges that most initiatives assessing the multiple impacts of energy system options will face – and thus the authors here provide a comprehensive guide to these key challenges that are important to pay attention to, as well as some solutions.

4.1.1 Baseline, additionality and context dependency

The size of the measured multiple impacts (MI) depends very strongly on a number of factors that are discussed briefly in this section. Some of these dependencies are already known from the assessment of direct benefits such as GHG savings (additionality and baselines), [67],[68],[69]others are encroaching newer grounds (context dependency)[70][62].

First of all, the declared size of the MI depends strongly on the baseline one compares it to – also influencing the so-called "additionality" – a well-established term in the GHG mitigation and energy efficiency literature[68], [69].The point is that when a low-carbon energy option/policy is assessed, it is crucial to only take the additional impacts into account, in order not to overestimate the impacts of the intervention but only the attributable change.

However, in the context of multiple impacts, the authors propose to distinguish three layers of additionality, each of which need to be met for a part of an impact to be calculated as an additional, new co- impact resulting from the action/policy

1. **Additionality of the low-carbon energy action/policy.** Is the low-carbon energy action/policy itself additional as compared to business-as-usual? Some investment in building-integrated renewables will inevitably occur, but how much of it can be attributed to a policy and how much would not have taken place without it?
2. **Additionality of the impact.** The additionality of the impact examined, induced by the low-carbon energy action or policy, needs to be thoroughly-checked. Additionality can be influenced by several issues. One of these is the initial state compared to

the (economic) social optimum. For instance, all investments in renewable energy and energy efficiency will result in reduced air pollution due to lower use of polluting fuels. However, if air quality and pollutant emission levels are regulated at a level that corresponds to the economic optimum, then additional reductions in emissions will not result in net economic gains at a societal level but in net losses, i.e. physical additionality of the impact does not translate into economic gains. This idea was demonstrated by Baumol and Oates,[71] in their seminal paper, but is typically not applied in empirical work on the estimation of costs and multiple benefits. Another issue, which influences the additionality of the impact is the interaction of different policy instruments/measures where the application of additional climate policy instruments/measures may not under certain circumstances result in additional impacts such as emission reductions

3. **Additionality compared to alternatives.** This particularly pertains to impacts resulting from investments. As money "does not fall from the sky" – any impact from a low-carbon energy investment needs to be compared to all potential alternative uses of the capital that is invested. For example, while major investments into deep retrofits will result in major gains in employment – such gains will also take place if the same capital is invested into other areas[37][72].Therefore, it is paramount that only the incremental impacts are taken into account in order not to overstate the impact. However, this requires the setting of baselines that do not normally form part of standard assessments of low-carbon energy options (e.g. when a renewable energy policy is assessed it is not normally expected that a baseline of where the state, private and household capital would have been invested forms part of the analysis).

As the additional impacts will likely be much smaller than the full impacts, these decisions about meeting additionality criteria, and therefore the baselines the actions/policies and impacts are compared to, make a fundamental difference in the overall value of the impacts. While these will typically have been conducted for (1) when clean energy options/policies are evaluated, (2) and (3) are much less standard, and are much more complex and challenging. The paper proposes that during the assessment of multiple impacts the test of meeting all three additionality layers is consistently carried out when calculating the size of an impact, or even before an impact is included in the calculations as a "new" multiple impact not yet covered by the traditional assessment methods (cf. also Table 7 in section 7).

There are also further contexts that can determine the outcome of the assessment of the multiple impacts. By the term "context" we refer to those variables which provide the background for a particular policy and, at the same time, are not directly related to the aim of the policy, but do, however, influence the outcome of policy actions. These include the broader socio-economic setting in which policies take place (e.g. age, income and health status of targeted population), cultural and behavioural attributes of the groups targeted by the policy, as well as the broader policy context (e.g. other environmental policies and their impacts), environmental conditions (e.g. air pollution levels, atmospheric conditions which impact the distribution of pollutants), market conditions (e.g. the price of energy) and other relevant context-related variables. As an example to highlight the crucial impact of contexts, Ürge-Vorsatz et al.[37][72] have found that during the evaluation of the employment effect of a large-scale deep residential retrofit programme, the assumptions on the financing scheme have a major influence on the outcome. In this study, a more generous state subsidy allowing households to be responsible for the repayment of a smaller share of intervention costs would have resulted in further induced employment arising from the additional household income and expenditure generated. In contrast, if a large share of the financing comes from loans, the employment impacts will be much smaller. In addition, net employment gains are expected if the intervention leverages previously unavailable capital from external sources (e.g. in an EU context, these would be competitively European funds allocated to Member States from Brussels). Different financing package assumptions all had different results on the employment impact, to a non-negligible order of magnitude.

Table 4: Identifies and classifies a few further contexts that matter while evaluating multiple impacts

Dependent variable (impact)	Context-dependencies
Disposable income and employment effect after energy efficiency actions in residential buildings	Details of financing schemes for retrofit (private and/or public funding; loan vs. savings, payback period) [37][72][73]
Level of energy savings or comfort benefits/rebound effect	Take back in comfort (increased indoor temperatures and share of space heated) and/or lower utility bills [26,74] are influenced by income levels, thermal comfort conditions before retrofits and the level of intervention – easy versus deep retrofits[48].
Number of traffic-related injuries and deaths due to modal shift in passenger transport to low(er) carbon intensity modes	Baseline level of modal split in the studied locality and the "safety in numbers" effect[75–77]; differences between short-term and long-term risks and effects [78], general transport/city infrastructure, local traffic, vehicle operation and transport safety regulations [76,78]; existence of pedestrian and cycling-friendly infrastructure [79], age of a person switching the transportation mode [80], cultural and behavioural norms in relation to cycling [77].
Avoided damage to human health, ecosystems and materials due to reduced air pollution emissions	Technological and fuel mix, geographic and climatic conditions, atmospheric transport, distribution of receptors and pollution sources, baseline air pollution concentrations, atmospheric chemistry, variation in receptor sensitivity, height of emission stack, air pollution control technologies [81–83], energy prices[30] , GDP, industrial structure [28], developed vs. developing country context [29]
Transaction costs	Type and size of technologies, regulatory frameworks, complexity of transactions, and the maturity of policy instruments reducing transaction costs[84]

4.1.2 Distributional aspects

Transition to a low-carbon economy is likely to cause a redistribution of wealth among and within states due to changing production and consumption patterns. However, transition to a more socially just and equal (global) society may not be automatic [85–87]. The improvements in social cohesion often rest on the assumption of a re-initiated economic growth and creation of green jobs. Meanwhile, some green economy policy initiatives may bear the risk of being socially regressive or endorsing the status quo. However, a much deeper social cohesion could be achieved, if the socially vulnerable groups were enabled to participate in and benefit from the low-carbon transition.

When assessing the multiple impacts of a low-carbon energy option or policy, looking at the total impacts may hide some impacts that are also important from social/economic perspectives in a green economy. While total impacts may be minor or none, the underlying distribution of positive and negative impacts may speak well to objectives of the (green) economy, such as poverty alleviation or improvement of social welfare, creation of "green" jobs rather than "polluting" ones, creation of local or rural employment rather than "exportable" jobs, or just more centralised, urban jobs, etc. Some countries also wish to develop some regions more than others do.

Therefore, it is important that the assessment of the multiple impacts is set up in a way that they can capture these distributional aspects of the multiple impacts, and not only the totals (see also the discussion on geographical and temporal scales).

As an example, energy efficiency in the residential building sector offers synergies in tackling energy poverty and climate change and could contribute to improved welfare and social equality[72]. The biggest gains in social welfare are to be reaped when retrofits target those suffering from inadequate thermal comfort during the cold season and/or disproportionately high utility bills[88]. Despite their relevance to a part of the society only, social welfare gains (human health, comfort, productivity) account for a significant share of social benefits in country-level studies – 35%of net social benefits in Ireland [48], 16-19%of net social benefits in Hungary [89] and 40-50%of gross annual benefits by 2020 in the EU and Norway [46].

4.1.3 Perspectives

When evaluating the indirect impacts of clean energy options, the results will be different depending on the perspective one considers. Any cost-benefit analysis (CBA) will include different cost and benefit components depending on its evaluation perspective. From a range of possible perspectives, most research and policy practice apply either the societal and/or the investor/end-user perspective.[5] Table 5shows the most common multiple EE impacts and their relevance to these perspectives.

Table 5: Benefit and cost components of different evaluation perspectives

Evaluation perspective	Benefits	Costs
Investors/end-users	Energy cost savings (incl. taxes) Subsidies and other transfers Multiple benefits for investors/end-users • comfort gains • noise reduction • increased building value • health and well-being improvements • increased competitiveness • increased productivity	(Incremental) costs of energy efficiency actions (incl. taxes) Investment risk Multiple costs for investors, e.g. • transaction costs • opportunity costs
Society	Societal energy cost savings (excl. taxes/tariffs): avoidable long-run energy supply system costs Multiple benefits for society • reduced GHG emissions • reduced local pollutants • reduced use and import of resources • additional employment • positive effects on public budget • increased competitiveness • positive effects on the energy system (e.g. grid stability, reduced network losses, reduced energy wholesale prices, delaying or deferring system upgrades) • increased energy security • impacts on social welfare(e.g. higher disposable income, fuel poverty alleviation)	(Incremental) costs of energy efficiency actions (excl. taxes, subsidies and other transfers) Multiple costs for society, e.g. • policy implementation costs • transaction costs (reduced through policy implementation) • opportunity costs

Source: Based on CPUC [90] and NAPEE[91], own adaptations.

[5] Evaluations can also be undertaken from further perspectives, e.g. from the perspective of policy or programme providers such as utilities that are obligated in some jurisdictions to achieve certain levels of renewable energy supply or energy savings. Different evaluation perspectives in the field of energy efficiency are described in more detail e.g. in CPUC [90]or NAPEE[91].

From a societal point of view, net economic benefits of the implementation of a specific policy or technical action, i.e. social welfare gains, are assessed. Properly accounting forthe relevant societal co-benefits (cf. Table 5)is, therefore, crucial for any decision regarding a policy intervention.

Evaluations from an investor/end-user point of view weigh the costs of an efficiency action against its benefits to the individual investor. Analysing the net benefits to investors(cf. Table 5), this perspective reflects arguments and incentives for investing in certain technologies.

Evaluators also typically apply discount rates varying by perspective – lower rates for evaluations from the societal perspective and higher rates for investors[6](cf. eceee & Ecofys[92], BPIE, Fraunhofer ISI[93], Cambridge Econometrics[94]). However, it is important not to mix up transaction costs or non-economic barriers for investing in low-carbon technologies with discount rates [92]. In economic modelling, such as general equilibrium models, discount rates are often increased to model the current adoption rates of low-carbon technologies, because there is no other way to model transaction costs and barriers and receive adoptions rates reflecting current trends. However, this should not be misinterpreted as proof that all further low-carbon actions are not cost-effective. Such arbitrary discount rates disguise the actual cost-effectiveness of low-carbon investments[92]. There is ample proof that for many energy efficiency policies and programs, the total of (incremental) costs of energy efficiency actions, policy implementation costs, and remaining transaction costs is lower than the life-cycle energy cost savings, calculated at 'normal' societal or investor's discount rates, making the energy efficiency intervention cost-effective(cf. CPUC[95];Eoin Lees Energy,[96]). Any multiple impacts would then add to these results.

4.1.4 Lifecycle approach

For the assessment of multiple impacts of low-carbon energy options, ideally, their whole lifecycle impact is examined. However, this introduces another level of major complexity into their evaluation. Lifecycle modelling approaches are well established in environmental sciences (see also Guinee et al.[97], Finnveden et al. [98]and Thabrew et al.[99]) for the assessment of impacts products or services have over their lifetime. In the context of multiple benefits, different impacts can be calculated from the same data or aggregated for the purpose of decision-making (e.g. in multi-criteria analysis). When quantifying the impacts of low-carbon energy options in different lifecycle stages, positive benefits in one stage may (partly/fully) be compensated by negative effects in another. In this case, impacts occur which cannot directly be compared to the results of non-lifecycle methods without system expansion. In addition, baseline uncertainties usually increase, when attributional lifecycle approaches (LCA) of technology-based actions are embedded in a larger macroeconomic context. For example, feasible options and impacts for recycling at end-of-life depend (amongst others) on the scaling of action implementation, the costs of recycling, the spatial proximity of facilities and prices for virgin and secondary materials as well as their demand in other sectors. One possible solution to these challenges could be the application of consequential or hybrid LCA methods (c-LCA) because they integrate economic modelling with product-specific impacts (see also Igos et al.[100], Dandres et al.[101], Marvuglia et al. [102]and Earles et al.[103]).

[6] A further differentiation of discount rates is often made between investors in the commercial, industrial and residential sectors.

4.1.5 Geographical and temporal scales

Finding the appropriate geographical and temporal scales and units of analysis for the evaluation of the multiple impacts of the concrete policy/action are crucial, and need to be selected case by case. This is because the overall impact, and their distributional aspects, can very much depend on these choices (see above).For example, if employment effects are calculated, the total impacts, and their distribution especially, can very much depend on the geographical and temporal boundaries of the assessment as well as the units of analysis. How many of the jobs created/discontinued are within the examined area and how many are through exports/imports to the geographical area examined? Is the potential redistribution of employment matters in terms of rural to urban or vice versa, or from less developed areas to more developed ones? Can the jobs lost be immediately compensated by new employment, or is there a temporal mismatch? Even if long-term snapshot impacts are satisfactory, will there not be any shorter periods when there will be either major overshoots or major shortages caused on the labour market? Some studies (e.g. Zhang et al.[104]), show the importance of explicitly considering the geographic distribution of multiple impacts.

In order to answer such questions, it is crucial that the basic geographic and temporal unit of analysis are carefully chosen so that the results provide insights to such questions.

4.1.6 Economic feedbacks

Economic feedbacks, in the energy efficiency literature known as rebound effects, are highly relevant to any multiple impact evaluation and related decision-making processes[105][106][107]. Rebound effects describe the phenomenon that expected energy savings do not fully translate into actual savings because energy consumption increases due to economic feedbacks. Different types of rebound effect have been discussed in the literature ranging from economic direct and indirect effects on the micro level (e.g. consumer, companies) to macroeconomic effects (for an overview see e.g. Greening et al [108], Sorrell[106], van den Bergh,[109]). The magnitudes of estimates vary highly depending on the system boundaries and applied methods.[7]The concept can also be applied to non-energy resources.

Although rebound effects are considered unintended and negative[105][110], in a multiple impact framework, the linked impacts may be welcome by policy (anticipated or unanticipated). An illustrative example is energy-efficient building renovation making higher indoor-temperatures affordable, causing a “rebound” effect (lower energy savings), but at the same time higher comfort and health benefits [111][26][27]. Higher “rebound” effects can be expected for housing retrofits if people live in energy poverty [112]. Therefore, depending on the scope of the study and on the available data on types of energy deprivation, rates for “rebound” effects (or comfort gains) could be included in an ex-ante assessment.[8] Besides social welfare, macroeconomic benefits can also be expected to be tied to rebound effects. Other

[7]e.g. estimates of the direct rebound effect (increased demand for the same energy service) in space heating alone vary between 1.4 % and 60 %, with most reliable estimated between 10 to 30 % according to Sorrell, [106]. The quality and reliability of the estimates steeply decrease for indirect (other energy services), and economy-wide/macroeconomic estimates as these are much more complex to estimate empirically as well as model-based (cf. Gillingham et al.[153]).

[8] On the other hand, [72] argue that forgone energy savings when solving energy poverty should not be labeled as rebound effect due to human health implications, and due to the fact that in the case of suppressed energy service levels the partial purpose of the policy is to provide full access to energy services, or, more broadly, to improve social welfare, rather than saving energy.

impact categories seem to be affected by rebound effects, but are not directly tied to them (e.g. improved outdoor air quality). The following table gives the first overview of rebound effects in relation to the defined MI categories.

Summing up, economic feedbacks are proven to happen and hence need to be addressed to account for trade-offs between savings of energy and intended benefits in a decision-making framework. The challenge is to find proper—but currently missing—correction factors linked to benefits of improvement actions. The first step to obtaining these is to define impact pathways (cf. below). Even the magnitudes of effects for single actions are currently controversially discussed among experts.

Table 6: First overview of the rebound effect and MI relation

Air pollution	Lower energy savings due to rebound effects affect air pollution and sub-impacts, but no induced trade-off between the potential benefit and energy savings is found.
Social welfare	An inverse relation/ trade-off between energy savings and social welfare may exist (e.g. improved comfort due to higher room temperatures).
Macroeconomic impacts	A trade-off between energy savings and macro benefits may exist (e.g. triggered by higher disposable income or lower production costs)
Resources	More resources are consumed if a rebound factor is assumed for actions. For indicating resource rebound effects other MI need to be taken into account (e.g. increased consumption due to changes in disposable income).
Energy system/security	The impact category might be directly affected by rebound, but does not create rebound effects (cf. air pollution).

4.2 Methodological challenges to aggregating quantified multiple impacts and integrating them with traditional energy option assessment methods

When evaluating the multiple impacts of a planned low-carbon energy action/policy, perhaps the most important challenges are faced during their integration: summing up the individually assessed impacts is not as straightforward as it may seem. This section reviews a few challenges that have been faced during the past and present research efforts of the authors on evaluating and integrating multiple impacts.

The Introduction section has detailed the lack of both empirical and theoretical literature on aggregating quantified multiple impacts. With regard to the little that exists, Edenhofer et al. [12]suggest to “choose a particular weighting of public policy objectives based on value judgments, i.e. a social welfare function, used for the evaluation of climate and energy policies. Climate change mitigation, energy security, green jobs, green growth, reduced local environmental damages and poverty reduction are potential public policy objectives highlighted by decision makers”. Others [113] have applied multi-criteria analysis to integrate the assessment of individual co-benefits into a single indicator. These approaches present their own challenges. While in the former case, the challenge is to identify a social welfare function, in the latter case the issue to address potential synergies and overlaps between different multiple impacts. Furthermore, none of these approaches seem to address the risk of over- or undercounting systematically.

4.2.1 Comprehensive accounting for all key MIs

The first difficulty is to identify all multiple impacts. If multiple impacts are to enter decision-making frameworks, it is crucial that an attempt is made to comprehensively account for them. As pointed out in this paper (and other papers see (Urge-Vorsatz et al.[114], Tirado Herrero et al. [27], Ryan & Campbell [6], Urge-Vorsatz et al.[72], (Urge-Vorsatz et al. [19], Von Stechow et al. [10]),many of the multiple impacts can be so substantial that they may become game-changers. However, if only a subset of them are assessed and integrated into the decision-making framework, this can result in biases. For example, it is typically not sufficient to only integrate co-benefits (or some of them) into such assessments, because in order to avoid a positive bias[9]all other indirect costs (risks, adverse side-effects, transaction costs, hidden costs, etc.) also need to enter the decision-making process. Equally, when only costs or risks are accounted for, it may create a negative bias, and the multiple benefits need to be integrated into the analysis to maintain a balanced assessment.

However, a comprehensive identification of the multiple impacts needs a systematic approach. While some disciplines can be utilised to identify a subset (such as environmental impact assessment, risk assessment, etc.), none will account for all societal/economic/environmental impacts because these extend over several fields of scientific enquiry.

This paper proposes a methodological framework that can help a comprehensive identification of all multiple impacts, although further work is needed on operationalizing and improving it.While the framework also cannot fully ensure that all multiple impacts are appropriately considered, it creates a more systematic and structured way of accounting for the various impacts that result from the action/policy and thus help make sure that all relevant impacts are identified. When the tool had been in regular use, typical patterns of impact pathway maps will have been formed, providing templates for new evaluations, and thus also a better prepared impact identification and assessment process, also facilitating a comprehensive coverage of multiple impacts.

For an easier identification of the key impacts to focus on, it will be beneficial if future assessments collect sufficient evidence for a trend- or other criteria-based grouping and prioritisation of multiple impacts according to certain variables (for instance types of actions, level of development, etc). The present amount of evidence is insufficient for forming even sound hypotheses on the importance of the various impacts as compared to each other, mostly because these are very action-, location- and other context-dependent. For instance, while literature has pointed to the importance of health gains as probably the most significant impact of high-efficiency cookstoves in least developed countries, these gains are unlikely to be large for appliance efficiency improvements in the most developed countries[115]. Therefore, for an *a priori* prioritisation of multiple impacts much more evidence is needed that is sufficiently granular to provide information on all the elements of the complex interaction-matrices that determine the overall importance of these impacts.

[9] The positive and negative here do not refer to value judgments, but cost vs. benefit ratios. If more benefits are evaluated than costs, a positive bias may be introduced to shift the net into more positive directions, while if more risks and side-effects are integrated, these will emphasise the cost aspects and will result in a negative bias for any policy/action.

4.3 Interactions among the MIs and avoiding double counting

MIs are not distinct and independent in nature but exist in a web of causality; they interact with each other in various ways, including cause and effect, reinforcements, attenuation and synergistic relationships. They may also overlap. This complexity presents a challenge for a rigorous assessment of individual MIs as well as for the aggregation of MIs. A number of studies have looked at similar (policy) interactions, (van Harmelen et al. [116], Amann et al. [117], Bollen, Heers and van der Zwaan, [118], however, studies in the context of an integrative assessment of MIs typically do not consider these interactions.

Both over- and underestimation of total benefits can result from summing separately estimated individual benefits. Pearce et al. [64]examine this issue in relation to ecosystems, and state that due to synergies summing separately estimated impacts results in underestimation of total benefits. Other authors (Sculpher[66], Wallace[119], Fu et al.[120], Bateman et al.[62])have debated the potential for overestimation of benefits resulting from double counting due to interaction of MIs. However, the few existing papers which have attempted to integrate separately estimated values for MIs (e.g. in this journal: Schweitzer and Tonn[24], or Wang et al.[121]) have not considered the impact of interactions among different MIs in the estimation of the total value for all MIs.

Overlaps are particularly pervasive related to health effects[66][122].For example, reduced air pollution resulting from investments in renewables or energy efficiency affects household comfort, peoples' health, and their productivity. These three types of multiple impacts at least partly overlap [19]. There will also be potential overlaps between valuations of morbidity and mortality effects and productivity impacts, if a monetary value is placed on lost productivity due to premature death, and additionally life years or quality-adjusted life years (QALY) are used as the measure of health, as both are valuing the loss in healthy time [66]. Fisk,[123]also discusses the overlaps between productivity benefits attributable to a decrease in 'Sick Building Syndrome' and health benefits from reduced incidence of asthma and allergies, both resulting from energy efficiency investments in buildings. Several studies, including Bhargava et al.[124] establish a causal link between improved health and GDP, which are both multiple impacts related to energy efficiency investment. Odrakiewicz,[125]explains the causal relationship between health and GDP through increased life expectancy and increased productivity. Measuring both the health and productivity benefits and the GDP impact of energy efficiency can, therefore, clearly result in the overestimation of the total impacts.

4.4 Physical metrics vs. monetization

Sustainable energy actions result in outcomes measured in a range of disparate units, such as quality-adjusted life years (QALYs), tonnes of physical resources saved or various metrics for improved energy security. In order to aggregate outcomes, or compare magnitudes of outcomes, a common metric is needed. This is typically done through monetization: valuing different physical metrics in terms of a common monetary metric; (Monetization has been criticised conceptuallyy on many grounds, for instance on that it purports to value phenomena, such as ecosystems, that are essentially "priceless" – see Luck et al.[126] and Gómez-Baggethun, E.& Ruiz-Pérez, M. [127].In addition, the resulting values can become very dependent on the valuation method used, or can become very controversial (such as a life in a developing country "worth" only a fraction of life in an industrialised country, etc.).Similar concerns are shared by the general public as there is a tendency to suspect that monetization may lead to the privatisation and commodification of non-markets goods and services. However, society is regularly faced with trade-offs of non-market benefits against other benefits, or against costs. Whether or not made explicit with a monetization, many political decisions include such trade-offs, which means some kind of valuation must be made. A monetization is in principle straightforward, but in practice, a number of difficulties arise. One issue is how to assess the value of an outcome for which there is no market – again, ecosystem services is a typical example. A range of techniques exist for such valuations (see Ürge-Vorsatz et al.[19]for an overview), but different techniques may yield substantially different results. In addition, most low-carbon energy actions are likely to have a time dimension. Therefore, a discount rate needs to be chosen for aggregating costs and benefits over time. There is a substantial literature on the theory and practice of discounting, but far from a consensus on what rates to use.

To mitigate the uncertainties and controversial aspects introduced by monetization, it is recommended that physical metrics are also reported along with monetized values where possible during the assessment of multiple impacts. If alternative, less controversial metrics, such as QALYs, can also serve as a sufficient "currency" into which all examined or important MIs can be translated, this can overcome some of these challenges although typically these will also fail to measure some of the important MIs.

4.5 Resource constraints, data needs and practicality

The tasks and challenges identified so far in this paper indicate that accounting for multiple impacts of low-carbon energy actions/policies in decision-making frameworks is crucial and needs to be conducted in a rigorous, careful and comprehensive manner. Otherwise, the resulting biases may cause more problems than not integrating the indirect effects, such as accusations of bias towards selective coverage of some impacts and thus distorting the outcomes in desired directions. However, conducting such evaluations is a very resource, data intensive and methodologically challenging task. Just evaluating a single impact such as the health or employment implications of a deep, whole-building retrofit mandate in a larger jurisdiction, will be a complex, data-intensive task. It is typically much more complex than conducting a cost-benefit analysis, that can often be more transferable: investments costs in the energy system are either comparable to other geographic locations or are often given or available; energy prices, while differing geographically and temporally, but not so substantially, as labour costs and unemployment, or outdoor air pollution levels. Therefore evaluating the multiple impacts with the currently existing methods and methodological frameworks needs more effort to account for the local context than for the direct cost-benefit analysis of low-carbon energy investments and is very data and resource intensive for each of the impacts.

At the same time, it is very unlikely that it is possible or feasible to conduct such detailed, comprehensive and rigorous assessments for each, even major, decision related to energy systems. Therefore, it is essential that the science of multiple impact evaluation develops significantly further and develops simplified methods, templates, database and tools that are easy (easier) and less data and resource intensive, but still enable the more informed, rigorous and comprehensive evaluation of energy system choices and policies.

Nevertheless, some of these trade-offs will remain in spite of any progress envisioned. These include the trade-offs between comprehensiveness and accuracy, analytical richness and resource (including financial, human and temporal) and data intensity. Due to the variability of the multiple impacts by many factors these trade-offs become particularly important in their assessment, and thus an ideal assessment considers these trade-offs explicitly, and balances these, such as time and resources available, with the ambition of the assessment, such as analytical richness and accuracy.

Admitting the complexity of the task ahead, the paper calls for more comprehensive assessments of low-carbon options capable of unveiling a range of impacts as wide as possible defined from a green economy or multiple impact perspective. However, the inherent limitations of ex-ante assessments must be acknowledged, whose results may differ substantially from real life outcomes as measured by ex-post analysis. In social cost-benefit analysis, such divergence can be attributed to four main types of error: omission errors, forecasting errors, measurement errors, and valuation errors [128]. These flaws and omissions are not negligible as they are conducive of suboptimal interventions from an aggregated social welfare perspective. Previous research shows examples of lack of or inaccurate ex-ante assessments resulting in the deployment of costly infrastructural developments not supported by an ex-post evaluation of costs and benefits [129][130].

5 Discussion

Proposed methodological framework for mitigating the methodological challenges to integration: the ‘multiple impact pathway’ approach

Recognising the magnitude of the challenges outlined above with regard to assessing and integrating the multiple impacts of sustainable energy transitions, and the lack of previously suggested comprehensive approaches to deal with these, this paper (i) proposes a methodological framework to deal with several of these challenges, especially the over/undercounting phenomenon; (ii) identifies a number of ways how the individual challenges above can be addressed.

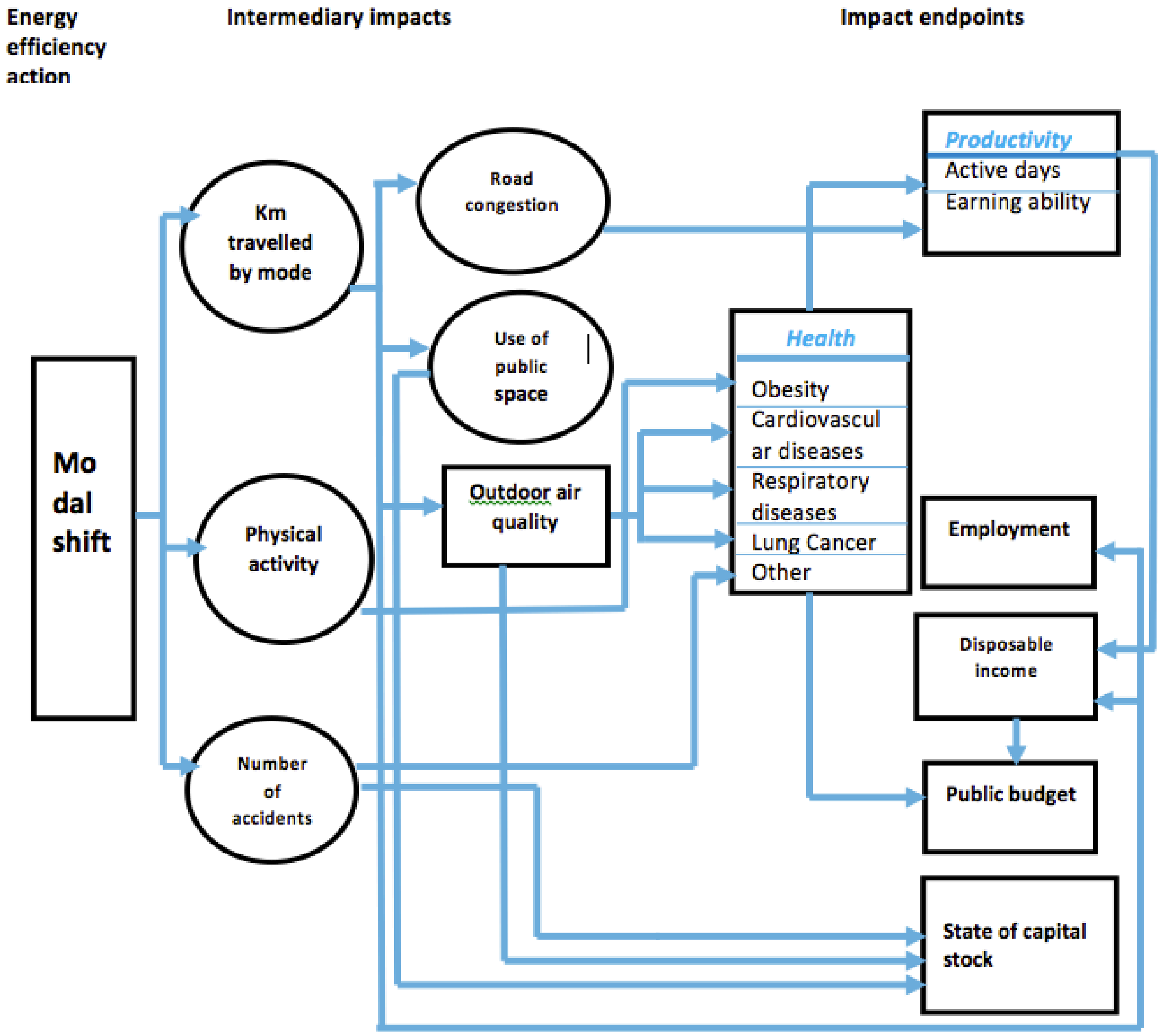
As stated before, because multiple impacts occur both as a result of a technological or other low-carbon energy action and of the policies that result in such actions, the methods proposed here are equally applicable to the assessment of technologies as well as policies for measuring progress towards a green economy.

The quantitative assessment framework proposed in this paper is based on the notion of *impact pathways*. This approach proposes the decomposition of the chain of effects linking a root cause or causes—the starting point of an action—all the way to the impact receptor or welfare endpoint, i.e. the impact that directly affects utility. The aim is to better identify and characterise how the impact unfolds, what different impacts occur as a result, and which factors enable or hamper its occurrence. It has been applied for a multitude of purposes such as the analysis of the influence of biofuel production in global markets Huang et al.[131], the environmental impact assessment of large dams[132]or the exploration of the links between globalization and negative trends in global health performance indicators[133]. In the field of applied energy research, a key implementation of this approach was initiated by the ExternE project for the monetary valuation of the externalities of energy provision technologies. In its methodology manual, impact pathways are defined as “the sequence of events linking a 'burden' to an 'impact' and [its] subsequent valuation. The methodology therefore proceeds sequentially through the pathway . It provides a logical and transparent way of quantifying externalities"(European Commission [134]). This idea is similar to that discussed by Shih and Tseng,[122] in this journal who limit their discussion to health impacts, and use concentration–response functions which consider the correlation between air pollutants, to avoid double counting of health impacts.

ExternE-like applications of the method have favoured a lineal representation of the impact pathway, e.g. from emissions to dispersion to impact and finally to (external) cost. However, reality is more complex as actions—such as investing in low-carbon technologies—often result in a variety of entangled effects. An enhanced quantitative assessment framework would need to pay attention to interactions across impact pathways and the dynamic nature of the process, among other aspects. Thus, a 'multiple impact pathways' approach is proposed with the aim of capturing the nuances and complexities of how impacts occur, thus anticipating connections, synergies, trade-offs, side effects, spillover effects, feedback loops, etc. As such, the 'multiple impact pathways' framework refers not only to both the negative and positive effects of low-carbon options but also to the multiplicity of impact categories/pathways and the interlinkages between them.

This complex mapping scheme enables the representation of the multiple impacts in a way that facilitates a more consistent and comprehensive accounting for them, as well as catalyses their integration in a way that minimises double counting and the under- and overestimation problems. If the framework is used in a rigorous, detailed and consistent manner to guide quantitative MI evaluations throughout the whole process, it facilitates their aggregation avoiding, or minimising these risks. It facilitates this in several ways. First, the framework enables, and forces, a systematic and comprehensive consideration of all potential multiple impacts. Second, if implemented rigorously, it maps the complex interactions and causal relationships among impacts. During aggregation, this helps in identifying if the impacts are additional, or partially or fully overlapping.

Figure 2: Illustration of the multiple impact pathway map approach on the case of modal shift in transport systems -- decomposing the pathways through which modal shift contributes to various multiple impacts



Describing the concept, application, strengths and limitations in detail will be done in another paper as these require much more space, so here only some key features are highlighted. The main idea is that the process how the multiple impacts are caused by the low-carbon energy action/policy is decomposed into as many pathways as can be differentiated, and each pathway into as many individual (sub)impact steps as key effects can be identified on the pathway. For example, a modal shift towards less energy intensive modes of transport, including public transport and non-motorised modes has three key primary consequences such as change in the distance travelled by each mode, change in physical activity and the number of accidents (Figure 2). These three impacts have further consequences, which ultimately leads to impact endpoints such as productivity, disposable income, employment and state of capital stock etc. Ideally, the impact end-points should be distinct, independent effects that conclude impact chains (impact pathways). Unfortunately, this is typically not possible because of the interconnectedness of the various effects, and end-points may be then defined by policy needs. For instance, in the concrete case air quality and health could be both chosen as impact end-points even if they are intermediary impacts in the chain of effects due to their importance to policy-making. Each arrow represents a distinct effect and therefore a distinct calculation, and probably the use of a distinct valuation method. For instance, the arrow between congestion to productivity refers to the fact that reduced congestion results in productivity gains due to more active time available for work (or other purposes), and will likely use evaluation techniques applied for congestion pricing.

Among many other advantages, the framework enables (a) a more systematic accounting for the various multiple impacts and thus reduced risk of missing impacts; (b) a much more systematic and precise calculation of the multiple impacts through the identification of the detailed steps and distinct effects; (c) the minimization of over- and undercounting. To justify the latter two: (b) the framework ensures that, for instance in the example given, productivity impacts are accounted for both through health effects (from several different impact pathways) and the congestion change effect. Double-counting is minimized (c) through a thorough utilization of the impact pathways: for instance, impacts that are included in the same impact pathway should not be added, only portions of them that are not translated in the calculations into the subsequent impact in the chain. For instance, only those aspects of air quality should be evaluated that have not been further counted through, for instance, infrastructure damages or health effects. While the framework also cannot fully ensure that all multiple impacts are appropriately considered, it creates a more systematic and structured way of accounting for the various impacts that result from the action/policy and thus help make sure that all relevant impacts are identified. When the tool had been in regular use, typical patterns of impact pathway maps will have been formed, providing templates for new evaluations, and thus also a better prepared impact identification and assessment process, also facilitating a comprehensive coverage of multiple impacts. For further details on the operationalization of the impact pathway map method and how it addresses more methodological challenges identified in this paper, please refer to the outcoming project reports in the COMBI project.

This overall framework can be then coupled with more specific recommendations for addressing the challenges identified in Sections 5 and 6 (see Table 1). These are based both on theory and on heuristic rules of thumb coming from the authors' experience as researchers.

Nevertheless, it is important to emphasise that the proposed framework is in its initial stages of development, and is only now being tried by some research groups. As its full operationalization for a specific case requires major analytical and empirical work, experience with it will accumulate slowly, and at this stage, it is challenging to see the full picture on its strengths and limitations.

Table 7. Recommended lines of action for the identified methodological challenges

Methodological challenges to the assessment of multiple impacts	Recommended line of action	Supporting bibliography and examples
Baseline, additionality and context dependency	Forecast the baseline incorporating as many dynamic variables as required to accurately quantify the true additional impact of low carbon options considering displacement effects (i.e. impacts taking place elsewhere). To the extent that is practical and feasible, consider multiple impact pathways in the baseline as well as in the scenario(s) under assessment.	Defining reference, status quo or baseline levels and of target levels (state achieved in different scenarios of proposed change) are necessary steps in cost-benefit analysis ([64][135]. Policy, technology, demographic, economic and 'natural' baselines can be considered [136]. Examples of global health benefits of low-carbon options using various emission reductions scenarios and mortality baselines are provided by Anenberg et al. [137]and West et al. [138].
Distributional aspects	Define how the assessment is positioned in respect to pre-existing inequalities, and whether and how the quantification methods will address them through adjustment factors. Bear in mind that applying no adjustment endorses the status quo by default.	Using distributional or welfare weights, Gini index and other poverty and inequality metrics is recommended to factor in differences in income levels across recipients of multiple impacts[136][139][140][141].Examples of the quantification of distributional effects in the assessment of multiple impacts can be seen in Nemet et al.[142] and Casillas and Kammen,[143].
Perspectives	Prioritise the societal perspective in the calculation of net gains and losses but also consider the standing of individual actors (investors/end-users) when a technology option results in sizeable private gains or losses that prevent or facilitate investments in low-carbon technologies.	Assuming that individuals' preferences can be aggregated and that beneficiaries from changes in baseline levels can compensate losers (Kaldors-Hicks criterion), welfare economics establishes that the preferred option is the one that maximises social discounted net benefits [64]. Stakeholder-level assessment is suggested as a complementary scale of analysis to understand the impacts on particularly important groups of society such as the poorest or key corporate actors.[19]
Lifecycle approach	Identify and assess impacts occurring before and after the operational lifetime of the technology options and include them in calculations accordingly, especially in the case of those involving large investments in physical capital with substantial embodied energy (e.g. energy-intensive processes of solar PV panels manufacturing) or with complex supply chains having effects across diverse geographical locations (e.g. components produced in the Global South and assembled and delivered in the Global North).	Life-cycle analysis (LCA) is the recommended approach in social cost-benefit analysis to make sure impacts brought about or avoided by the low-carbon option are measured across the entire life cycle of the investment [64][135]. Examples of multiple impact assessment of energy efficiency and renewable energy can be found in Arvesen and Hertwich,[144],Shih and Tseng [122], Xue et al.[145].
Geographical and temporal scales	Reflect on and identify key differences in environmental and socio-economic factors across locations if benefit transfer techniques are applied, paying special attention to income disparities with distributional implications. Consider that even if long-term timeframes are problematic because of the uncertainties surrounding forecasts and	Spatial heterogeneity in key factors such as the exposure and vulnerability of population is needed in geographically-explicit assessments of climate-related impacts– see Hill et al. [146] andHarlan and Ruddel,[147]). Despite controversies about the need to discount and the value of the discount rate, the economic literature shows a consensus towards positive discount rates that outweigh

	projections (e.g. in energy prices) the use of discount rates for temporal aggregation results in long-term effects having a smaller weight in net present values (NPV).	present vs. future impacts ([64].
Rebound effects	Account for rebound effects while considering interactions with other impact pathways. Rebound effect-induced additional energy use often results in enhanced wellbeing on additional endpoints (e.g. in the domestic energy use sector, these usually lead to improved comfort, especially among energy poor households).	Direct and indirect rebound effects are needed for a proper consideration of the dynamic effects of investing in low carbon options, as seen in the residential energy efficiency retrofits([112][148]. General equilibrium is a recommended quantitative assessment framework to fully capture rebound effects ([149].
Comprehensive accounting for all key multiple impacts Interactions among the multiple impacts and avoiding double counting	Prior to starting the quantitative assessment, map impact pathways, endpoints and interactions across pathways as extensively as possible while allowing for the emergence of unforeseen elements in later stages of the research. When faced with the risk of incurring in double counting, take a conservative approach to quantification in order not to undermine the credibility of the assessment.	Mapping multiple impacts, welfare change endpoints and pathways is recommended before quantification. Pre-assessment mapping also minimises the risk of double counting. Previous research provides a taxonomy of categories that can be used as a starting point for applied quantification exercises [6][19]
Physical metrics vs. monetization	When sufficient, use physical metrics for measuring impacts. When monetization is important as a common 'currency' to integrate the different impacts, systematically report on methodological dilemmas encountered. Report physical metrics and per unit monetary values whenever possible for the sake of clarity and replicability of the assessment. Remind the audience that monetary units reported are not market prices but a numeric estimate of net changes in aggregated societal welfare that allow summing up disparate impact typologies with a common measuring rod.	Ethical dilemmas surrounding methodologies for the monetary values of key non-market impacts such as changes in ecosystem services or morbidity and mortality rates is a recurrent debate in the literature – see Spangenberg and Settele,[150]and Söderholm and Sundqvist,[151]. Workflows in quantitative assessment frameworks such as cost-benefit analysis require impacts to be measured in physical units before estimating monetary values [64], which allows the researcher to decide what type of results to be provided
Resource constraints, data needs and practicality	Based on the mapping of pathways and endpoints, take appropriate decisions on which aspects to focus on during quantitative assessment in order to capture the most significant effects of the examined technology options. Do not systematically disregard less well-researched pathways and favour a flexible engagement that leaves space to incorporating impacts initially considered as less relevant.	In the applied research framework that guides the assessment of multiple impacts, data collection can be seen as a costly activity that is worthwhile to the extent that the information will serve to influence decisions [152].

6 Conclusions

Future directions for assessing low-carbon energy options towards a green economy

The ex-ante assessment of different low-carbon energy options and policies towards a green economy is crucial in order to make optimal energy choices for society. These are typically conducted based on the CBA of direct costs and benefits; while the paper demonstrates that including the multiple impacts—costs as well as benefits—in the quantitative analyses can be game-changing. However, this task is very complex and so far lacks appropriately elaborated methodologies that, among others, (a) systematically account for all impacts and (b) systematically and consistently examine the interactions among them and integrate them in a manner that avoids over- and undercounting issues.

The purpose of the paper was to fill several knowledge gaps by identifying the key additional challenges to systematically identifying, quantifying and integrating multiple impacts of low-carbon energy options related to the assessment of the progress towards a green economy; identify solutions to these; and within that, propose a methodological framework that systematically addresses several of these challenges.

The paper first showed that multiple impacts have been indicated to account for a large share of direct benefits, as much as 53 to 350% of direct benefits in NPV calculations based on the few studies available from which such ratios can be derived. Then, the paper identified additionality, baseline and contextual dependency issues; economic feedback issues; appropriate choice of evaluation perspectives and geographic and temporal scales; aspirations for and challenges to applying a lifecycle approach, as well as addressing distributional aspects as the key challenges to the optimal assessment of the individual impacts. Within this, the paper identified three layers of additionality that need to be met in order for an impact's value to be counted as a multiple benefit not yet accounted for in the traditional assessments. Focusing on the challenges to the integration of multiple impacts, the paper pointed to difficulties with systematically identifying and accounting for all multiple impacts; under- and overcounting risks due to the interaction of impacts; choosing appropriate metrics for the synthesis; and finally the physical, resource and practical constraints of conducting such complex assessments.

After collecting existing methodological remedies to mitigate these challenges, the paper proposed a new methodological framework for the assessment of multiple impacts that is particularly applicable for a systematic accounting for the multiple impacts, systematic mapping of their interactions, and their consistent integration, avoiding as much as possible over- and undercounting concerns.

Nevertheless, the framework is still in its infancy, and much further development and scientific scrutiny is needed in order for it to be able to serve its ultimate purpose – advancing the assessment of low-carbon energy options towards the green economy. However, innovation in new methods and tools cannot stop here. The paper pointed to the complexity and substantial data, resource and time requirements of integrating multiple impacts into the economic assessment of energy options and policies, therefore, substantially simplified methods and tools, requiring a fraction of these needs, are essential before the integration of multiple impacts into energy option and policy assessment can routinely extend to multiple impacts. For allowing ex-post evaluation, there is also a strong need for the integration of respective research/evaluation schemes into policy evaluation from the very beginning (before enactment).

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