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Systematic review of the outcomes and trade-offs of ten types of decarbonization policy instruments

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The literature evaluating the technical and socioeconomic outcomes of policy instruments used to support the transition to low-carbon economies is neither easily accessible nor comparable and often provides conflicting results. We develop and implement a framework to systematically review and synthesize the impact of ten types of decarbonization policy instruments on seven technical and socioeconomic outcomes. Our systematic review shows that the selected types of regulatory and economic and financial instruments are generally associated with positive impacts on environmental, technological and innovation outcomes. Several instruments are often associated with short-term negative impacts on competitiveness and distributional outcomes. We discuss how these trade-offs can be reduced or transformed into co-benefits by designing research and development and government procurement, deployment policies, carbon pricing and trading. We show how specific design features can promote competitiveness and reduce negative distributional impacts, particularly for small firms. An online interactive Decarbonisation Policy Evaluation Tool allows further analysis of the evidence.

More-stringent GHG emission reduction targets than those currently implied by the nationally determined contributions are needed to reduce the dramatic risks associated with global warming[1]. Achieving such targets will require additional and more-ambitious decarbonization policies[2,3].

Yet climate change mitigation is not the only goal of decarbonization policies and often not the main one[4–6]. Several other goals are pursued alongside climate ambitions, such as economic competitiveness, affordability and fairness. Indeed, the potential negative impacts of decarbonization policies on key socioeconomic outcomes is often cited as the main reason for not pursuing mitigation efforts[7]. It is therefore not surprising that the European Union's recent 'Green Deal' sets the objective of mitigating climate change impacts in the most cost-effective and equitable manner, without hurting the overall economic competitiveness[8,9].

Understanding how specific decarbonization policy instruments can be designed to minimize possible trade-offs among different outcomes—that is, how they can yield 'co-benefits'[10–12]—is important to inform and support a just, fast and sustainable transition. Available research evaluates the effectiveness of different types of policy instruments on different outcomes across various jurisdictions, sectors, technologies and geographic contexts, but a systematic assessment is lacking. In this exploratory analysis, we address this gap.

First, we develop a rigorous and transparent framework for the systematic review of the peer-reviewed body of evidence on the impact of ten widely used types of decarbonization policy instruments on a broad set of socioeconomic outcomes. Systematic reviews (SRs) are often used to inform further research and policy decisions[13]. They are a consistent, transparent and widely used methodology to identify, analyse and interpret the existing evidence from multiple disciplines, relying on different methodologies and focusing on different geographic and temporal contexts. The types of policy instruments analysed are building codes and standards; renewable energy obligations (or renewable portfolio standards, RPS); government procurement; public research and development (R&D) funding; feed-in tariffs or premiums (FITs/FIPs); energy auctions; energy taxes and tax exemptions ('taxes and tax exemptions' henceforth); GHG emissions allowance trading schemes (or cap-and-trade systems); tradable green certificates (TGC); and white certificates (or energy efficiency standards). The seven categories of outcomes analysed are environmental, technological, cost-related, innovation, competitiveness, distributional and other social outcomes. The application of this framework in the SR yielded 211 scientific articles and reports (see brief mention in Methods and full description in Supplementary Sections I and II).

Second, we code, summarize and interpret the often-conflicting evidence emerging from the SR on the positive, null or negative impact of the ten policy instruments on the seven outcomes. We develop an 'agreement indicator' (see Methods) to characterize the level of agreement across evaluations. Recognizing that SRs are not without limitations, we complement this paper with the online Decarbonisation Policy Evaluation Tool (DPET), which collects all the coded literature on which this analysis is based. The DPET allows the reader to independently explore the evidence across different dimensions (countries, sectors, methodologies and/or metrics) and includes additional functionalities not described here (for example, coding the 'strength of evidence').

Third, we illustrate the practical implications of our SR, analysis framework and online tool. We discuss how policy instrument design can reduce the negative competitiveness and distributional impacts on small and medium-sized enterprises (SMEs) identified for three types of economic policy instruments: direct investments, renewable energy deployment subsidies and carbon pricing.

Description of the sample for systematic review

The sample of publications and evaluations in our SR, by policy instrument, is summarized in Fig. 1 (see Supplementary Section I for definitions). Taxes and tax exemptions have been the focus of the largest number of evaluations, followed closely by FITs/FIPs,

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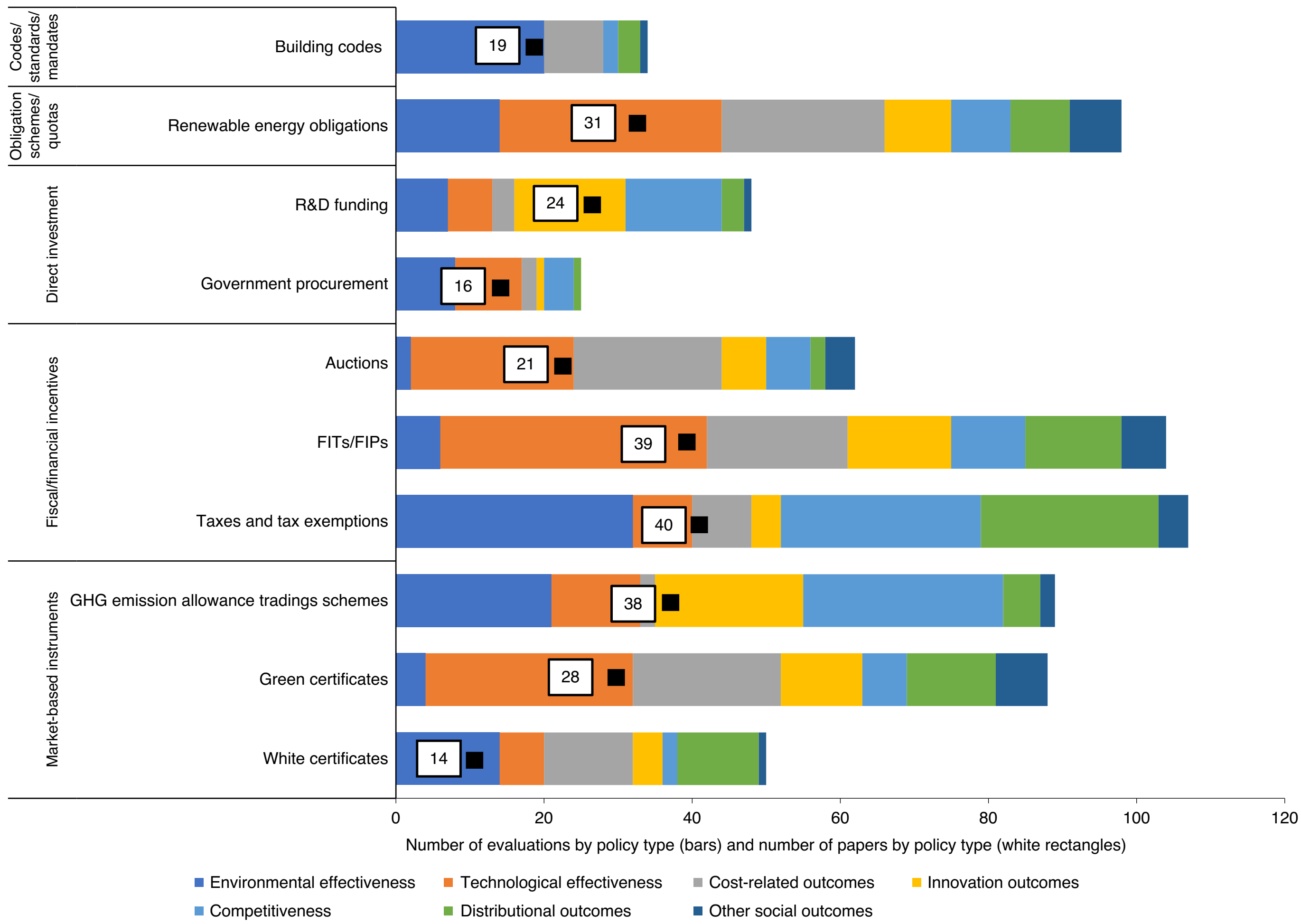


Fig. 1 | Evaluations by type of policy instrument and outcome. The number of publications providing evidence for each type of policy instrument is shown in the white rectangles with black borders. The colour bars refer to the total number of evaluations available for each type of instrument. Note that the total number of publications in the white rectangles by type of policy instrument is 270 and not 211 because there are publications that assess more than one instrument.

RPS, GHG emission allowance trading schemes and green certificates. The most-evaluated instruments have been studied on a wider range of geographical, temporal, technological and policy design contexts and using a wider range of research methodologies. For each type of policy instrument, evaluations are not uniformly distributed across outcomes. For example, most of the analyses of building codes explore environmental effects, while those of green certificates or RPS focus mostly on technological effectiveness and cost-related outcomes. A larger number of papers and reports study environmental and technological outcomes, as opposed to other outcomes (Supplementary Section III).

Altogether, the included papers cover more than 50 countries (Fig. 2). Most papers analyse policy instruments and outcomes at the national level in Organisation for Economic Co-operation and Development (OECD) countries, with the United States, the United Kingdom and several EU countries—Germany, Italy, France, Denmark, the Netherlands and Spain—being most frequently studied. A very small number of papers focus on countries in sub-Saharan Africa—with the exception of South Africa—and in the Middle East, highlighting a large gap in the geographic coverage of the literature. Supplementary Section II and the DPET provide more details on the publications that resulted from the SR, for example, sectors and jurisdictions, journals, academic disciplines and research methods.

Trade-offs in decarbonization policy implementation

Our proposed 'agreement indicator' characterizes the level of agreement in the evidence and is calculated for each of the ten policy instruments across the seven outcomes (see Fig. 3 and Methods for details). Its values range from 0.33, indicating a maximum level of disagreement, to 1.00 for full agreement. Two key findings emerge. First, there is high agreement on the positive impact of all policy instruments on environmental and, to a lesser extent, technological outcomes. The indicator for environmental outcomes ranges from 0.51 for R&D funding to 1.00 for auctions and white certificates. This is not surprising given that the alleged first goal of decarbonization policies is reducing GHG emissions.

Second, many instruments are associated with some negative impacts on competitiveness and distributional outcomes. In most of these cases, agreement on the direction of impact (whether positive, negative or null) is low.

Here we discuss the results for the competitiveness and distributional outcomes. Results for the other five outcomes are shown in Extended Data Figs. 1–5 and discussed in Supplementary Section III.

Competitiveness trade-offs. Widely used metrics to assess the impact of decarbonization policy instruments on competitiveness include firm productivity, job creation and private investments, among others. Most evaluations rely on ex post methods and

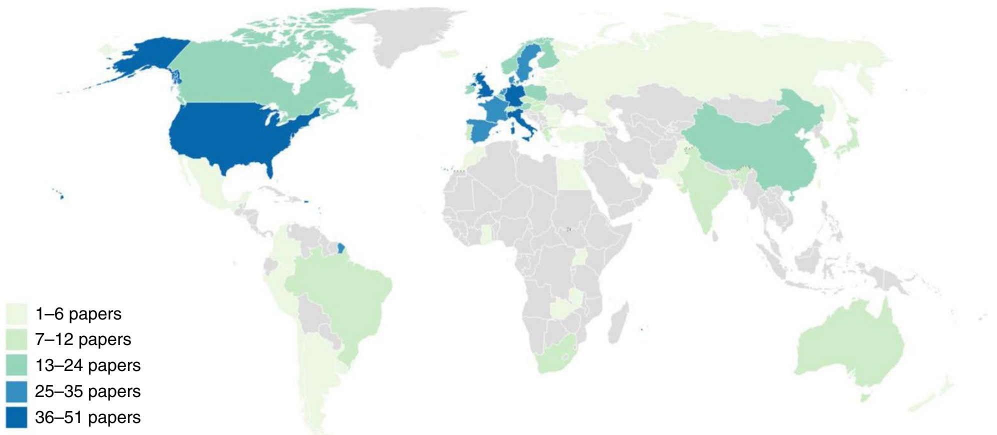


Fig. 2 | Geographical scope of the publications identified in the systematic review. Some publications cover more than one country. In addition to the publications shown in this figure by country, the review identified 5 theoretical publications with a global geographical scope, 5 publications with a focus on OECD countries as a whole and 27 publications analysing the European Union as a whole.

provide inconclusive results. Of the 105 evaluations on competitiveness across the 10 types of instruments, 32% report positive effects and 39% report no impact. This is tantamount to saying that the majority (71%) of the evaluations did not identify competitiveness trade-offs (Fig. 4). This, coupled with the fact that the ten policy instruments are associated with generally positive environmental outcomes, is somewhat encouraging. The remaining 29% of the evaluations report negative competitiveness impacts, suggesting the existence of competitiveness trade-offs, at least in the short to medium term and for some groups of actors. The disagreement in the literature for each policy instrument cannot be attributed solely to differences in research methodologies, as shown in Fig. 4.

Both energy taxes and GHG emission trading systems present mixed evidence on competitiveness outcomes, with negative impacts in 41% and 30% of the evaluations, respectively. Conversely, around 59% and 70% of the evaluations report null or positive impacts, respectively. Some papers document negative competitiveness impacts, such as lower employment rates[14–17], due to increasing energy costs, particularly for energy-intensive industries and industries exposed to international trade. Closely comparing studies that have negative impact with those that have null/positive impact shows that policy instrument design, and in particular the existence of recycling mechanisms and exemptions[18], is an important factor contributing to the different outcomes[17], alongside sectoral specificities.

Note that we analyse only the results of publications assessing energy taxes (carbon, air pollution and fuel taxes) as detailed in Supplementary Section I. These policy instruments are part of a larger environmental tax and tax exemption category and make up almost 80% of the total tax collection from environmental taxes in, for example, the European Union[19]. Out of the 40 papers covering energy taxes, 27 cover carbon taxes and 15 cover a mixture of local air pollution and fuel taxes. We do not find systematic differences in competitiveness and distributional outcomes between carbon and fuel taxes.

R&D public expenditures have a positive impact on competitiveness metrics, including the export dynamics of environmental goods[20] and the ability to attract venture capital funding in the clean-tech sector[21,22]. The level of agreement is high.

Government procurement is not associated with competitiveness impacts[23,24] according to two out of four evaluations. The other two evaluations, which come from a single publication[25], report conflicting results: a positive impact and a negative impact. All of these evaluations use a qualitative approach.

The evidence regarding policy instruments that subsidize renewable energy generation is mixed. This can be attributed to the type of proxy used to measure competitiveness, for example the concentration of the market around the bigger producers or specific technologies[26,27] and/or other metrics of domestic competitiveness[21,28,29]. For building codes and white certificates, research is scant and no conclusions can be drawn.

Distributional trade-offs. Analysing whether a particular type of policy instrument has negative distributional impacts is necessary not only because of ethical concerns, but also to identify potential barriers to acceptability and public support and, hence, to the long-term sustainability of the instrument[30,31]. The variables used to this end in the literature include consumers' energy bills, the total energy budget of either consumers or governments, the distribution of costs, and consumer and producer surplus, among others. This SR identifies many instances of negative short- or medium-term distributional impacts of policies supporting the deployment of renewable energy, as shown for RPS, FIT/FIPs and TGC[32–35] (Fig. 5).

For example, 12 of the 13 evaluations assessing the distributional outcomes of FITs identify regressive effects[34,36,37]. These results are not driven by the most frequently studied countries (Spain and Germany). Rather, they are consistent across many of the 40 geographical contexts for which evidence is available. For example, the analyses of distributional outcomes of FITs in Spain and Germany (four publications each); the United Kingdom (three); Denmark, Italy, France and Greece (two each); and China (one) all signal some negative impacts. For TGCs, 83% of the 12 evaluations report negative impacts, while only 17% report positive impacts. There is only one evaluation of the distributional impact of government procurement, and there are only two evaluations of the distributional impact of auctions. The evidence on the impact of renewable energy obligations is evenly split: half of the eight evaluations report positive impacts and half negative impacts. In this case, negative distributional impacts arise from the fewer opportunities or lower commercial prospects for small producers and developers when compared with larger ones.

Energy taxes have been the focus of 24 evaluations, using both quantitative and ex ante approaches. The majority of these evaluations (63%) report negative distributional impacts while 25% and 13% report positive and no impacts, respectively. Some papers concluded that rural areas suffer higher welfare losses from energy taxes compared with urban areas[38,39]. Mixed evidence emerges from the few analyses of the distributional effects of these taxes. Some papers show less negative distributional impact for fuel taxes and local air pollution (for example, NO_x and SO_2) compared with carbon taxes[17,39]. Others present similar results for carbon and fuel taxes, especially when recycling mechanisms are not in place[40,41]. The five evaluations on the distributional impacts of GHG emissions allowance schemes show a high level of disagreement.

Policy instruments for building-sector decarbonization, that is, white certificates (11 evaluations) and building codes (3 evaluations), are associated mostly with positive distributional impacts. The cost burden of white certificates[42] does not appear to negatively impact low-income households[43]. Thus, white certificates emerge as fair instruments[24] since the cost of energy savings does not disproportionately burden low-income end users[44]. Only one and three evaluations are available on the distributional impacts of R&D funding and government procurement, respectively.

Overcoming trade-offs in climate change mitigation

The results of our SR point to short- to medium-term competitiveness and distributional trade-offs for all instruments in specific circumstances. Importantly, the disagreement across studies identified in Figs. 3–5 cannot be attributed solely to differences in research methodology, the technology or sector studied, or temporal, geographical and institutional contexts.

In a few instances, the disagreement on the impact of a given financial or economic policy instrument stems from differences in policy instrument design. This point is illustrated in the following by focusing on R&D grants and government procurement (direct investment instruments), FITs and auctions (fiscal/financial instruments) and carbon-pricing and trading schemes (in the fiscal/financial instruments and market-based instruments categories, respectively). The discussion highlights how, in specific cases, these instruments are associated with negative outcomes on small firms or new entrants and positive outcomes on large firms or incumbents. It also describes the design features that are associated with the lowest trade-offs between outcomes, or the highest co-benefits across competitiveness and distributional outcomes, as well as cost-related and innovation outcomes. See Supplementary Section IV for discussions of additional examples.

The policy/outcome/direction of impact framework and the coded SR results in the online DPET can be used to further explore the results discussed so far and to explore additional functionalities (Supplementary Section V). For example, the DPET allows users to analyse the importance of factors such as research methodology and geographical context, to focus on specific countries, metrics or sectors, the level of agreement, and to identify knowledge gaps.

R&D and government procurement to facilitate innovation in SMEs. Recent literature indicates that the design of R&D funding schemes can help foster firm-level competitiveness outcomes beyond the positive impact on innovation outcomes[21,22,45]. Government R&D funding programmes targeting small companies or those in early stages of development help attract other funding sources and advance small firm competitiveness[21]. Howell[22] shows that stepped R&D grants for small firms advance both innovation and competitiveness outcomes. Stricter audit or review processes after a first phase of funding help ensure the additionality of more public R&D funding in a second phase[22]. For small companies, R&D grants tend to be a complementary instrument to R&D tax credits[45], a complementarity that does not clearly emerge for large firms. A combination of direct R&D funding and R&D tax credits may stimulate higher R&D private expenditures than the application of each policy instrument independently[45]. This SR supports the notion that public R&D funding specifically targeting small firms can improve competitiveness outcomes, although the evidence is small and concentrated in the United States and the United Kingdom.

Government procurement can also promote innovation and competitiveness in small firms. Importantly, it can be used by local and regional jurisdictions to target localized problems for firms, such as facilitating access to new markets[25,46–50]. In some cases, the use of public procurement in local and regional jurisdictions resulted in positive competitiveness and innovation outcomes through the creation of market opportunities, particularly for small and medium-sized firms in economically stressed areas[51]. Given the challenges smaller companies face in getting novel sustainable products into the market, government procurement programmes should include flexible design features. Provisions that facilitate the involvement of small firms and overcome potential trade-offs include targeted procurement programmes or the possibility to adjust contracts and bids on a one-by-one basis to remove barriers specific to small firms[52]. For example, the procurement process for climate-friendly lighting in Kolding (Denmark) was designed with two tiers, one of them specifically tailored for small firms.

Predictable and adjustable FITs and auctions tailored to support technology deployment. FIT designs that are not characterized by enough flexibility and responsiveness to the evolution of technology and project costs are associated with negative cost-related outcomes (Supplementary Section III). FITs designed to be technology specific and include adjustable, but predictable, tariff values mitigate negative cost-related and distributional outcomes[53]. Yet, as discussed in Supplementary Section III, 'tighter' tariffs may lower incentives to innovate. Thus, policy makers should consider creating additional incentives for innovation either on top of the FIT pricing or/and through complementary policies[54–56].

FITs tailored to facilitate a smaller size and more-dispersed power generation facilities[57] can be beneficial in two ways. First, smaller and more-dispersed projects create markets and improve competitiveness for small producers. Second, smaller projects can improve public acceptance by, for example, mitigating the well-known 'not in my backyard' syndrome[57,58].

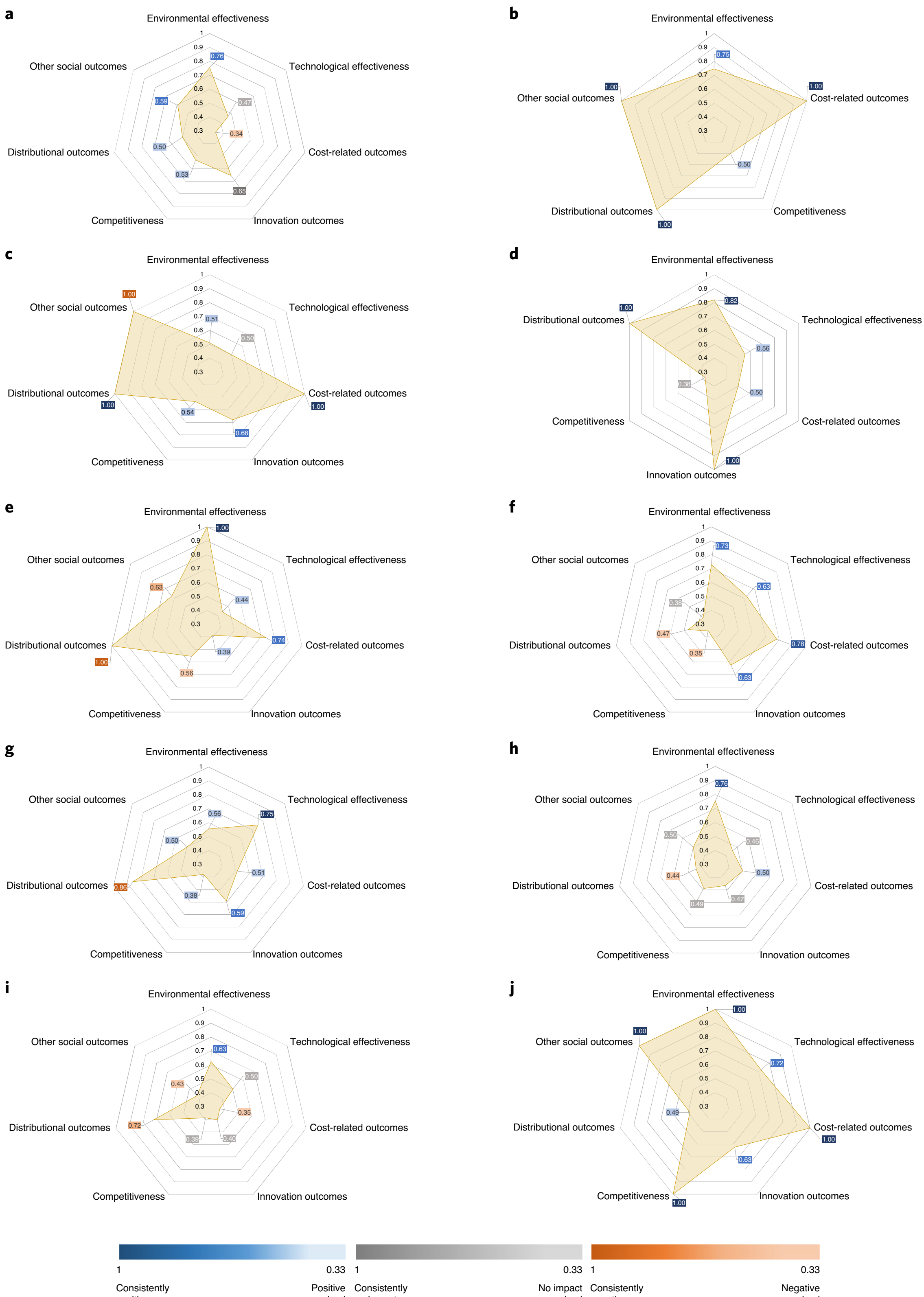
Renewable energy auctions are generally associated with positive impacts on cost-related outcomes and on competitiveness outcomes for large firms[59,60]. Yet competitiveness impacts on small firms or new entrants can be negative due to the tighter cost margins of auction schemes when compared with FITs[26,36,61]. To overcome this, governments can design specific auctions for small producers or support their participation through additional means.

The combination of different policy instruments, for example, FITs plus auctions, can also mobilize different producers and technologies in different stages of development to simultaneously reduce costs, support competitiveness for both large and small firms and reduce negative short-term impacts on small producers[57,58].

Fig. 3 | Level of agreement in the literature by type of policy instrument and outcome. a, Renewable portfolio standards (*n* = 98). **b**, Building codes (*n* = 34). **c**, R&D funding (*n* = 48). **d**, Government procurement (*n* = 25). **e**, Auctions (*n* = 62). **f**, Taxes and tax exemptions (*n* = 107). **g**, FITs/FIPs (*n* = 104). **h**, GHG emission trading schemes (*n* = 89). **i**, Tradable green certificates (*n* = 88). **j**, White certificates (*n* = 50). For each type of policy instrument, the number of sides in the polygon reflects the number of outcomes for which there was at least one evaluation available. The label states the agreement indicator for each outcome by type of instrument. The colour of the label reflects the directionality of the policy instrument impact: a blue oblong label reflects primarily a positive impact (as defined in the Methods); an orange label reflects primarily a negative impact; grey reflects that the majority of the evidence points to no or negligible impact. The darkness of the colour and the distance to the centre of the figure are proportional to the level of agreement, as measured by the agreement indicator, ranging from 0.33 (full disagreement) to 1.00 (full agreement). The bottom of the figure includes a colour legend. For each panel, *n* denotes the number of evaluations per policy instrument underlying the figure.

Recycling mechanisms and compensatory non-environmental exemptions in carbon pricing. Carbon pricing and trading instruments, whether as taxes or markets for permits, show the highest levels of disagreement on competitiveness and distributional outcomes. Competitiveness outcomes are most often negative for energy-intensive export industries. By contrast, the impact of carbon pricing on the competitiveness outcome for the power sector is generally positive. This is probably because the power sector is generally more oriented towards domestic markets[62,63].

The negative impacts on some competitiveness outcomes can be mitigated, at least partially, with compensatory non-environmental exemptions and revenue recycling mechanisms[64–67]. Tax exemptions can reduce competitiveness trade-offs and have the additional benefit of being relatively simple and easy to implement. They also have



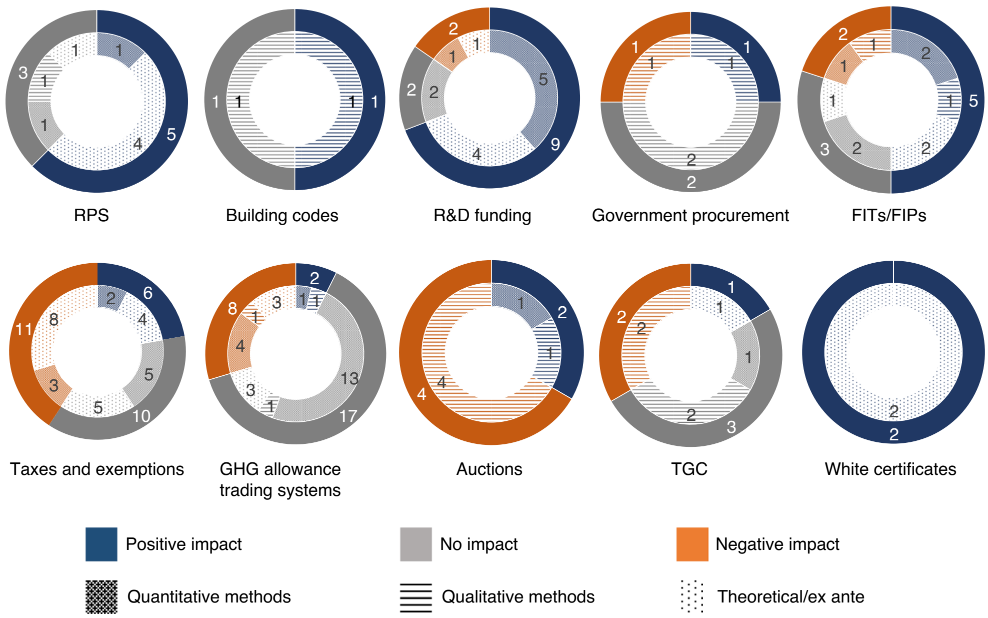


Fig. 4 | Direction of the impact of ten policy instruments on the competitiveness policy outcome. The circles summarize the aggregated assessment from the systematic review. The outer circles represent the number of positive-impact (blue), no-impact (grey) and negative-impact (orange) evaluations by type of policy instrument. The inner circles represent the type of methodology that was used in the evaluations determining the different impacts. The checkered pattern denotes quantitative methodologies, the striped pattern represents qualitative methodologies and the dotted pattern represents theoretical literature and models and/or ex ante evaluations. For a list of the competitiveness outcome indicators included in the publications analysed, see Supplementary Fig. 2 in Supplementary Section I.

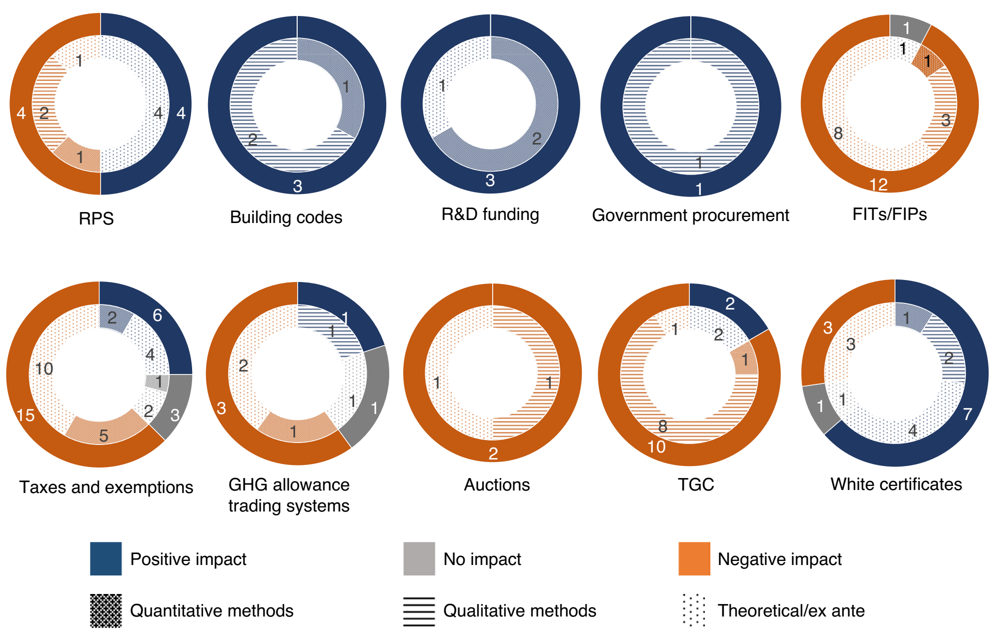


Fig. 5 | Direction of the impact of ten policy instruments on the distributional policy outcome. The circles summarize the aggregated assessment from the systematic literature review. The outer circles represent the number of positive-impact (blue), no-impact (grey) and negative-impact (orange) evaluations found for each type of policy instrument. The inner circles represent the type of methodology that was used in the evaluations determining the different impacts. The checkered pattern denotes quantitative methodologies, the striped pattern represents qualitative methodologies and the dotted pattern represents theoretical literature and models and/or ex ante evaluations. For a list of the distributional outcome indicators included in the publications analysed, see Supplementary Fig. 2 in Supplementary Section I.

comparatively high political acceptability[24]. These exemptions can be of two types. First, sectors and companies subject to emission trading systems can be exempt from carbon taxes[38,66]. Second, if the uncertainty around carbon prices is too large for businesses to put in place upgrades without losing competitiveness internationally, income tax reliefs or exemptions can be applied to natural and legal persons who invested in the energy efficiency of processes, installations or buildings[24].

Recycling mechanisms are key to mitigate negative outcomes for small firms because tax revenues can be used to reduce corporate taxes or social security contributions. To avoid the emergence of competitiveness trade-offs for small companies, energy tax reforms can modify the object of taxation rather than increase tax benefits[68]. Several examples of tax designs reducing burdens for small companies are already in place in some OECD and European countries[64]. For example, the energy taxation reform introduced in Austria in 2004 with the aim of increasing taxes on natural gas, oil and coal, included a reduction of corporate taxes and other tax incentives for SMEs. Similarly, in 1996, Denmark increased industrial energy tax rates (it introduced a tax for sulfur and one for natural gas) but also included a recycling mechanism in the form of a reduction in employers' social security contributions. Additional subsidies for energy efficiency taxes in SMEs were also included[64,67]. In British Columbia, the corporate income tax rate was also reduced in 2008 from 4.5% to 2.5% for small businesses. These tax designs have lower distributional and competitiveness trade-offs for small companies[68].

Most evaluations available agree that carbon taxes without exemptions and revenue recycling are regressive and have negative distributional impacts, above all for SMEs[64,65,67,68]. When energy tax revenues are used to reduce payroll taxes, and if wage–price inflation is prevented, substantial short- to medium-term reductions in GHG emissions, small gains in employment and marginal variations in production are likely[65].

Discussion and conclusions

This analysis contributes to the literature on policy instrument evaluation as well as to debates regarding policy instrument selection and design in the context of promoting a fair, equitable and economically sustainable transition to a net-zero future[3].

There is a large body of literature evaluating the impact of different types of policy instruments on environmental, technological, innovation, competitiveness and distributional outcomes. This SR shows that the literature on competitiveness and distributional outcomes is characterized by a high level of disagreement. In some contexts, and under specific policy instrument designs, there are short- to medium-term trade-offs between decarbonization and other socioeconomic goals. The most frequently occurring trade-offs between environmental outcomes and competitiveness and distributional outcomes are for taxes, TGCs, GHG emission allowance trading schemes and FITs. Disagreement in the literature can be partly explained by differences in the research method employed and/or other contextual features, including the technology covered or the actor or sector investigated. Yet in many cases, policy instrument design differences explain the contradictory results emerging from this analysis.

This paper discusses three specific cases—direct government investments, renewable energy deployment subsidies and carbon pricing—in which design elements can help overcome a particular type of trade-off, namely, the negative competitiveness outcomes on small firms. For public R&D funding and government procurement, innovation and competitiveness of SMEs can be promoted through specific mechanisms for allocating and monitoring R&D and targeting small firms. Short-term negative impacts of deployment subsidies on cost-related outcomes, competitiveness and distributional outcomes for SMEs can be mitigated through tailored, predictable and adjustable support levels and possibly a combination of different types of fiscal and financial instruments supporting deployment. For carbon-pricing schemes, recycling mechanisms and compensatory non-environmental exemptions can improve the prospects of SMEs as they try to enter new markets.

One important caveat is that this analysis does not imply that any future implementation of the ten different types of decarbonization policy instruments reviewed would necessarily result in the same positive, null or negative impacts documented here. Changes in the context of policy implementation—such as increased policy ambition and policy targets, cost reductions, competition and industry structure, among others—probably affect outcomes. Rather than trying to predict the future, our method takes the available body of evidence and uses it to identify the type of instruments and outcomes more frequently associated with the existence of negative trade-offs. It also allows to illustrate which design features may help mitigate the possible negative effect of a subset of decarbonization policy instruments on key socioeconomic outcomes beyond climate mitigation goals.

Different institutional settings, technologies and industrial structures and policy instrument designs may allow co-benefits across outcomes that may not have been documented or previously experienced, and therefore not reflected in our SR. While this is purely speculative, changes in institutional contexts may lead to different approaches and to different outcomes when thinking about ambitious sustainability transitions and more-stringent targets[69,70]. Regardless, to reach the goal of a net-zero carbon economy by 2050 with an eye on the Paris Agreement and the Sustainable Development Goals, additional and more-ambitious policy instruments are essential. Taking stock of previous experiences with different types of policy instruments across outcomes is a useful step to strengthen the knowledge and support effective policy making[71].

We nonetheless acknowledge that systematic reviews are not free from limitations, including the identification and the selection of the studies and the well-known issue of publication bias. Our approach, analysing the direction of the impact on the different outcomes counting across the various studies, is common in environmental sciences where the metrics for different outcomes cannot be easily homogenized[72], as is the case in our analysis. Yet it does not allow assessment of the magnitude of the impact (through a meta-analysis, for example) on the outcome—a factor that researchers and policy makers are rightly also interested in[72,73].

The systematic and transparent application of our framework and review, combined with the various robustness checks performed (Supplementary Section II), contributes to reducing potential biases that may emerge from considering a narrower set of metrics, research methods or countries. The online DPET, which allows for a thorough exploration of the coverage of the sample, makes it also possible to dive more deeply into the evidence.

This analysis represents a first step; other methodologies, such as cross-national panel data analyses across all the policy instruments and countries, using consistent outcome variables and metrics, may be more suitable to address questions about the magnitude of the impact of the different types of policy instruments. Note that, unlike qualitative case studies, which are also included in the SR, these cross-national panel methods have difficulties accounting for other institutional and instrument design factors unless their focus is very narrow. Indeed, a limited number of the papers included in the SR, typically covering one policy instrument and outcome, used such an approach. Thus, analyses using cross-national panel methods consistently across all countries to explore the impact of policy instruments on outcomes or metrics represent a worthwhile effort in the future to complement this work. We also note that future work could also compare the ex post evidence available from this SR with existing modelling results on different policy instrument outcomes as part of integrated assessment models, for example. This would allow the identification of differences and could lead to improving the modelling of policy instruments. Along the same lines, future work could compare the insights from policy reports, usually targeting policy makers, with results from academic literature. These analyses are necessary to identify and correct possible biases that could explain differences between projections/simulations of the impact of policy instruments and their actual performance and between the production of evidence targeted to diverse audiences.

Finally, a non-trivial contribution of our analysis is the identification of policy instruments, outcomes and research questions for which there is very little or no evidence, either empirical or theoretical. This, combined with the analysis of the geographic coverage of the evidence, helps identify important research gaps (discussed in more detail in Supplementary Section VI) and suggests avenues for future research, including expanding the scope of the policy instruments covered and strengthening interdisciplinary dialogues on specificities of policy instrument designs and their outcomes in different sectoral and geographical contexts. Filling such gaps will further improve understanding of how to promote a net-zero transition.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-020-00971-x.

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Methods

Analysis framework. We developed a framework for the systematic evaluation of different types of policy instruments for a net-zero future and used it to develop the search strategy of an SR of the literature[74]. In our context, the framework used to develop the SR methodology includes four components: classification of decarbonization policy instruments, criteria and outcomes for the evaluation of policy instruments, systematic review process, and analysis of the direction of the impact and the level of agreement in the evidence.

Classification of decarbonization policy instruments. We classify public policy instruments in three broad categories[75–78]: regulatory instruments, economic and financial instruments and soft instruments. This is largely consistent with the most common approach adopted in the economic literature[79,80]. We further detail 8 meso-level policy types and 21 specific policy instruments. Our typology is based on previous categorizations of policy instruments[81–85].

For the purpose of this analysis, we focus on (1) regulatory instruments and (2) economic and financial instruments. Within regulatory instruments and economic and financial instruments, we select ten types of policy instruments: building codes and standards; RPS; government procurement; R&D funding; FITs/FIPs; energy auctions; energy taxes and tax exemptions; GHG emissions allowance trading schemes (or cap-and-trade systems); green certificates; and white certificates (or energy efficiency portfolio standards). Detailed explanation on the selection of the policy instruments and their definitions are included in Supplementary Section I.

Criteria and outcomes for the evaluation of policy instruments. This paper uses an SR methodology to assess the evidence available regarding the impact of ten types of regulatory and economic and financial decarbonization policy instruments on a wide set of environmental, technological and socioeconomic outcomes[86]. As part of the development of the framework for analysis, we consider the following seven types of outcomes: environmental effectiveness outcomes, technological effectiveness outcomes, cost-related outcomes, innovation outcomes, competitiveness outcomes, distributional outcomes and other social outcomes. Detailed definitions (Supplementary Table 2) and further explanation on the rationale behind choosing these outcomes are presented in Supplementary Section I.

SR process. The SR process is detailed in Supplementary Section II and includes the identification of the elements of the CIMO framework, a structured and contextual approach widely used for systematic literature reviews in social sciences[87], the definition of the question to investigate, the inclusion and exclusion criteria to establish the search strategy and the set of publications included, and a description of the final sample of publications based on disciplines, journals, research methods, jurisdiction and sector. Details on how the outcomes from the publications were analysed are also included.

Analysis of the direction of the impact and the level of agreement in the evidence. The application of our SR of the literature, including inclusion and exclusion criteria detailed in Supplementary Section II, yielded 211 publications focused on the policy instruments and outcomes detailed in Supplementary Figs. 1 and 2. We developed processes for coding the papers to indicate the direction of the impact of each policy instrument of each outcome covered in the publications and a method for assessing the level of agreement between documents (See Supplementary Section VII for a full list of the publications derived from the SR process).

Analysis of the direction of the impact of the policy instrument. Experienced researchers hand coded each paper to indicate whether the specific policy instrument(s) analysed were found to have a positive, null or negative impact on the specific outcomes (for full details on the coding process, including double coding, see Supplementary Section II). A given policy instrument evaluation was categorized as evidence of a 'positive impact' when the instrument being investigated was associated with a 'socially desirable' change in the given outcome from a policy perspective. Examples of positive impacts include a reduction in energy consumption, which would fall under the environmental effectiveness outcome, or an increase in patenting, which would fall under the innovation outcome. Conversely, we assigned 'negative impact' when the implementation of the policy instrument was associated with undesirable effects from a policy perspective. Examples of negative impacts include an increase in the price of the electricity paid by consumers, which falls in the distributional outcome category (for example, most of these papers point out that such price increases disproportionately affect those at the low end of the income distribution because they spend a greater fraction of their income on energy expenses) or a decrease in employment rates, which falls in the competitiveness outcome category. 'No impact' indicated that the paper did not establish a link between the policy instrument and the outcome analysed.

Our coding resulted in 705 distinct policy instrument evaluations. This number is far higher than the number of publications in our sample because many papers analyse more than one type of policy instrument and/or more than one outcome. In addition, in some papers the impacts identified vary depending on the technology, the sector or the context.

We include additional discussions on the coding of papers in Supplementary Section II.

Assessing the level of agreement. To summarize the level of agreement regarding the direction of the impact of a given policy instrument on a given outcome, we develop an 'agreement indicator' inspired by the Herfindhal index[88]. This indicator is calculated as follows:

$$H = \sum_{i=1}^{3} s_i^2 \quad (1)$$

where s_i is the share of positive-, negative- or no-impact evaluations by outcome and policy instrument, and i is the number of potential outcomes, that is, positive, negative or no impact. By design, the index moves from 0.33 (from a full level of disagreement regarding the impact of each policy instrument individually on a particular outcome) to 1.00 (a full level of agreement, indicating that 100% of all the evaluations of a policy instrument on an outcome are, for example, pointing to a positive impact). For example, if 70% of the evaluations of a specific policy instrument report a positive impact on a specific outcome, and 30% report a negative impact, the index equals $0.7^2+0.3^2=0.58$. This indicates broadly consistent, but not universal, evidence of a positive impact. Conversely, if 70% of the evaluations of a specific policy instrument report a negative impact on a specific outcome, and 30% report a positive effect, the index still equals $0.3^2+0.7^2=0.58$. In this case, however, the indicator suggests broadly consistent, but not universal, evidence of a negative impact. In other words, the indicator is positive by construction but may indicate a positive, a negative or no impact depending on which of the three impacts is most prevalent in percentage terms from the evidence available.

If more than 90% of the evaluations by outcome and policy instrument point to the same type of impact (positive, negative or null), the evidence will be considered completely consistent. From 70% to 89%, it will be largely consistent, and below 70% is mixed.

Data availability

The details of the study design, all data and information compiled for this research and the procedures for their analysis are detailed in this published article and its Supplementary Information files. The datasets with the coding of the evidence generated during this study (including those available in the Supplementary Information) are available from the corresponding author upon request. The coded evidence can also be accessed free of charge through the online 'Decarbonisation Policy Evaluation Tool' (https://dpet.innopahts.eu). This tool allows the reader to explore additional research questions or different aspects of the evidence. This tool includes various functionalities, including (1) allowing the user to filter different evidence according to the research method, (2) weighing the evidence using weights specified by the user, (3) filtering by policy instrument or outcome and (4) reading the systematic coding of the papers along different categories, including jurisdiction, time period, additional details regarding the data and research methods, the sector and so on. Source data are provided with this paper.

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Author contributions
C.P., L.D.A. and E.V. designed the systematic review. C.P. implemented the design of the systematic review, identifying the sample of papers included in the study. C.P., L.D.A. and E.V. coded the papers in the review, analysed the results and wrote the manuscript.

Competing interests
The authors declare no competing interests.

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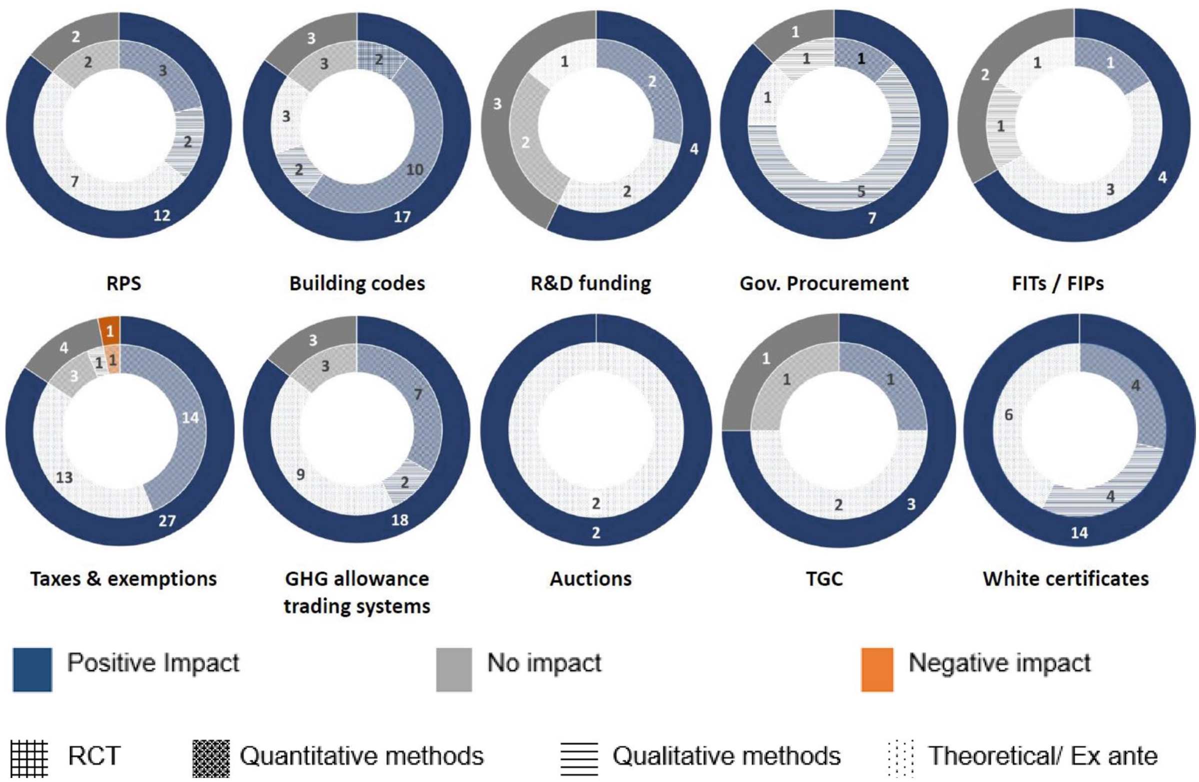
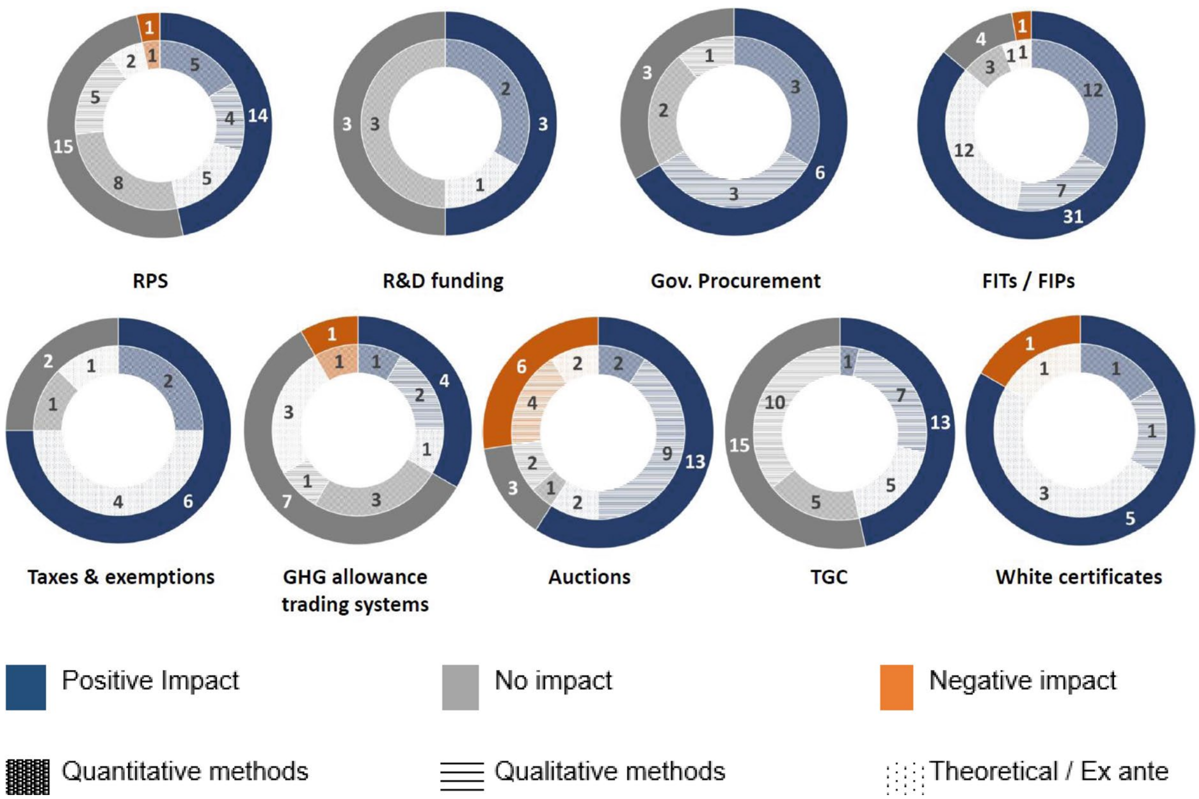
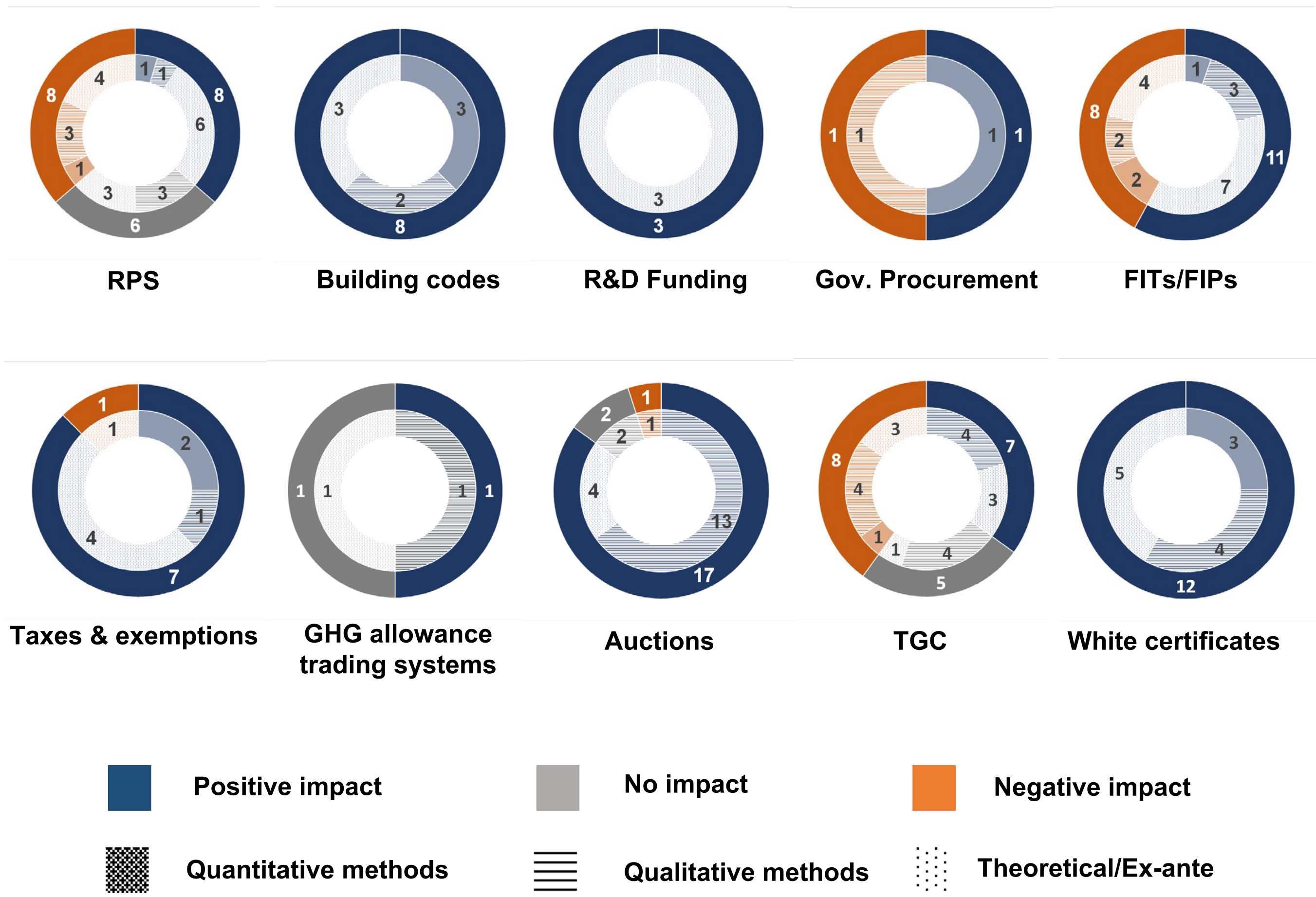


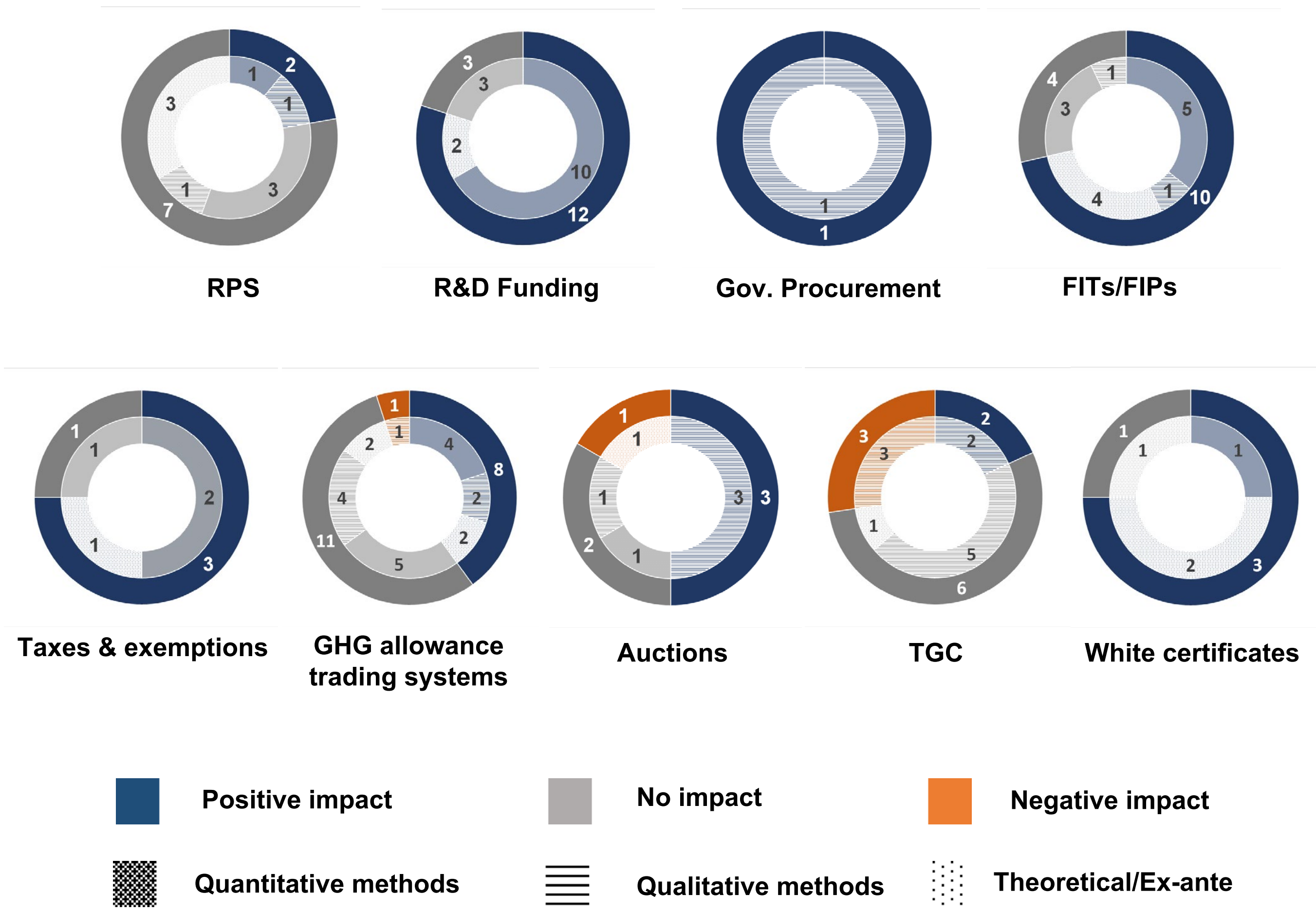
Extended Data Fig. 1 | Aggregated assessment of the impact of the ten policy instruments on the environmental effectiveness outcome. The circles summarize the aggregated assessment from the systematic literature review. The outer circles represent the number of positive impact (blue), no impact (grey) and negative impact (orange) evaluations by type of policy instrument. The inner circles represent the type of methodology that was used in the evaluations determining the different impacts. The grid pattern denotes controlled trial methodologies, the checkered pattern denotes quantitative methodologies, the striped pattern represents qualitative methodologies, and the dotted pattern represents theoretical literature and models and/or ex-ante evaluations. For a list of the environmental effectiveness outcome indicators included in the publications analysed, see Supplementary Fig. 2 in Supplementary Section I.



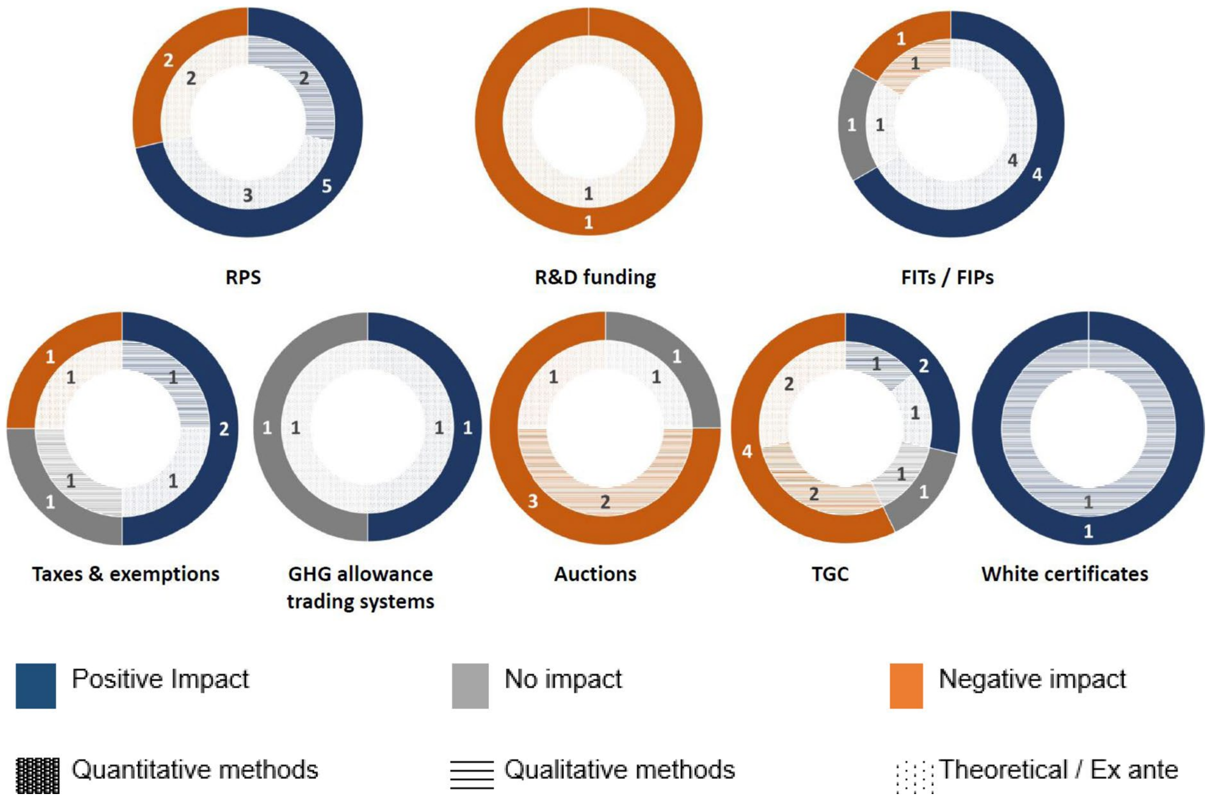
Extended Data Fig. 2 | Aggregated assessment of the impact of the ten policy instruments on the technological effectiveness outcome. The circles summarize the aggregated assessment from the systematic literature review. The outer circles represent the number of positive impact (blue), no impact (grey) and negative impact (orange) evaluations by type of policy instrument. The inner circles represent the type of methodology that was used in the evaluations determining the different impacts. The checkered pattern denotes quantitative methodologies, the striped pattern represents qualitative methodologies, and the dotted pattern represents theoretical literature and models and/or ex-ante evaluations. For a list of the technological effectiveness outcome indicators included in the publications analysed, see Supplementary Fig. 2 in Supplementary Section I.



Extended Data Fig. 3 | Aggregated assessment of the impact of the ten policy instruments on the cost-related outcomes. The circles summarize the aggregated assessment from the systematic literature review. The outer circles represent the number of positive impact (blue), no impact (grey) and negative impact (orange) evaluations by type of policy instrument. The inner circles represent the type of methodology that was used in the evaluations determining the different impacts. The checkered pattern denotes quantitative methodologies, the striped pattern represents qualitative methodologies, and the dotted pattern represents theoretical literature and models and/or ex-ante evaluations. For a list of the cost-related outcome indicators included in the publications analysed, see Supplementary Fig. 2 in Supplementary Section I.



Extended Data Fig. 4 | Aggregated assessment of the impact of the ten policy instruments on the innovation outcomes. The circles summarize the aggregated assessment from the systematic literature review. The outer circles represent the number of positive impact (blue), no impact (grey) and negative impact (orange) evaluations by type of policy instrument. The inner circles represent the type of methodology that was used in the evaluations determining the different impacts. The checkered pattern denotes quantitative methodologies, the striped pattern represents qualitative methodologies, and the dotted pattern represents theoretical literature and models and/or ex-ante evaluations. For a list of the innovation outcome indicators included in the publications analysed, see Supplementary Fig. 2 in Supplementary Section I.



Extended Data Fig. 5 | Aggregated assessment of the impact of the ten policy instruments on the other social outcomes. The circles summarize the aggregated assessment from the systematic literature review. The outer circles represent the number of positive impact (blue), no impact (grey) and negative impact (orange) evaluations by type of policy instrument. The inner circles represent the type of methodology that was used in the evaluations determining the different impacts. The checkered pattern denotes quantitative methodologies, the striped pattern represents qualitative methodologies, and the dotted pattern represents theoretical literature and models and/or ex-ante evaluations. For a list of the other social outcome indicators included in the publications analysed, see Supplementary Fig. 2 in Supplementary Section I.