ECONOMICS OF ENERGY INNOVATION AND SYSTEM TRANSITION

Underestimation of the Impacts of Decarbonisation Policies on Innovation to Create Domestic Growth Opportunities

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ABSTRACT

This paper shows that the basis for decision making in many climate, energy and innovation policies is biased against correctly estimating the opportunities and economic benefits from decarbonisation policies. The three main reasons are: the underestimation of technological change by experts and most quantitative approaches; the new evidence regarding the positive impact of decarbonisation policies across all stages of innovation, not just diffusion; and the underrepresentation of innovation processes in economic models.

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Key messages

1. Empirical evidence from policies ‘on the ground’ confirms the positive impacts of decarbonisation policies on technology innovation outcomes. Positive impacts are consistently found when considering indicators like renewable energy deployment.

2. Policy evaluations available also show a positive impact of a wide range of decarbonisation policies on different technology innovation indicators spanning the whole innovation process. Positive impacts are found for: increased private R&D investments, patenting, emergence of new green products and eco-innovations, and technology cost reductions over time.

3. Existing technoeconomic models to date have rightly focussed on capturing the effect of some decarbonization policies on technology deployment. However, other innovation outcomes are less represented in the models. No model currently represents all of the ways in which, according to the empirical literature, policy affects innovation. Structural change in the energy sector is leading to a general underestimation of technological change and the potential economic benefits of decarbonisation policies supporting innovation.

4. Model-based technology forecasting methods are more accurate than estimates by experts. However, all forecasting methods underestimate technological progress in almost all technologies, likely as a result of structural change across the energy sector due to widespread policies, social and market forces. This can lead to systematic bias in policy making.

5. Public R&D investments and Feed-in tariffs (FITs) are the two types of policy instruments for which the strongest evidence is available regarding their positive impact on different technology and energy innovation indicators. These policy instruments are not often represented in the models. This insight offers a clear opportunity to improve modelling tools.

6. Other policy instruments for which there is evidence of positive impacts on innovation that would benefit from more attention from a modelling perspective are: Renewable energy (RE) auctions, Energy efficiency standards (EES) and White certificates, Renewable Portfolio Standards (RPS), and Grants and subsidies.

1. Background

Over the past decade, innovation has outpaced expert forecasts. Data-driven methods are more accurate, but they still generally underestimate innovation in the energy sector.

In the past couple of decades, technological innovation in the energy space has progressed faster than what experts had predicted in all the areas for which data is available apart from nuclear power (Meng et al., 2021)[1]. However, additional technological innovation in areas ranging from renewable energy generation, integration and storage, electric vehicles, marine shipping and aviation, energy efficiency in buildings, to energy intensive manufacturing industries, among others; is essential to mitigate climate change (IPCC, 2018)[2]. Crucially, domestic innovation policies will also be essential to make sure that different countries seize the opportunities for growth and new markets associated with the energy transition and that those countries have access to resilient, affordable, and healthy energy systems. In that sense, there are strong economic and societal rationales for using policies to promote technological innovation and influence its direction in the energy and climate space.

Yet, model-based scenario analyses used by governments and supranational organisations—including the IPCC—to support the decisions and analysis of policy options to get to net zero emissions by 2050 and/or to meet the goals of the Paris agreement; often fall short when it comes to representing the decarbonisation policies. To give an example, the extent to which integrated models and cost-benefit analysis of regulations or policies underestimate technological innovation would create a bias against supporting innovation in the policy making process. Models using cost inputs based on expert assessments would underestimate technological change compared to model-based methods, which researchers in the consortium have shown are more accurate (Meng et al., 2021; see also Appendix, Fig. A2).

This paper provides evidence on the systematic underestimation of the impacts of decarbonisation policies on innovation in modelling tools aimed at informing policy and investment decisions. It brings together the results of two major systematic literature reviews on the evidence about the impact of different policy instruments on different innovation indicators, which include insights from a set of 94 papers[3]. This evidence is

[1] Meng, J., Way, R., Verdolini, E., & Anadon, L. D. (2021). Comparing expert elicitation and model-based probabilistic technology cost forecasts for the energy transition. *PNAS*, 118(27), e1917165118.

[2] *IPCC Special Report on Global Warming of 1.5 °C* (eds Masson-Delmotte, V. et al.) (WMO, 2018).

[3] Insights were produced by synthesizing evidence from two systematic reviews published by EEIST researchers: a) Peñasco, C., Anadón, L.D. & Verdolini, E. (2021). *Systematic review of the outcomes and trade-offs of ten types of decarbonization policy instruments*. Nat. Clim. Chang. 11: 257–265. https://doi.org/10.1038/s41558-020-00971-x. The paper has a Decarbonization Policy Evaluation Tool: http://dpet.innopaths.eu/#/. b) Grubb et al. (2012). *Induced innovation in energy technologies and systems: a review of evidence and potential implications for CO2 mitigation*. Env. Res. Lett. 16:043007. https://doi.org/10.1088/1748-9326/abde07. The evidence used in this paper covers more than 30 countries; see details of the geographical coverage in the Appendix.

then directly contrasted with the results of a survey of 16 technoeconomic models[4] developed to support the energy and climate policy decision making process around the world.

2. Innovation process

Understanding innovation needs the consideration of indicators covering the full innovation process. Covering only one of the indicators would provide an incomplete picture.

Clean energy innovation is a complex non-linear multi-stage process that follows five distinct stages—research, development, demonstration, market formation, and diffusion—interconnected through multiple feedback loops (see Fig. 1) (Grübler et al., 2012)[5].

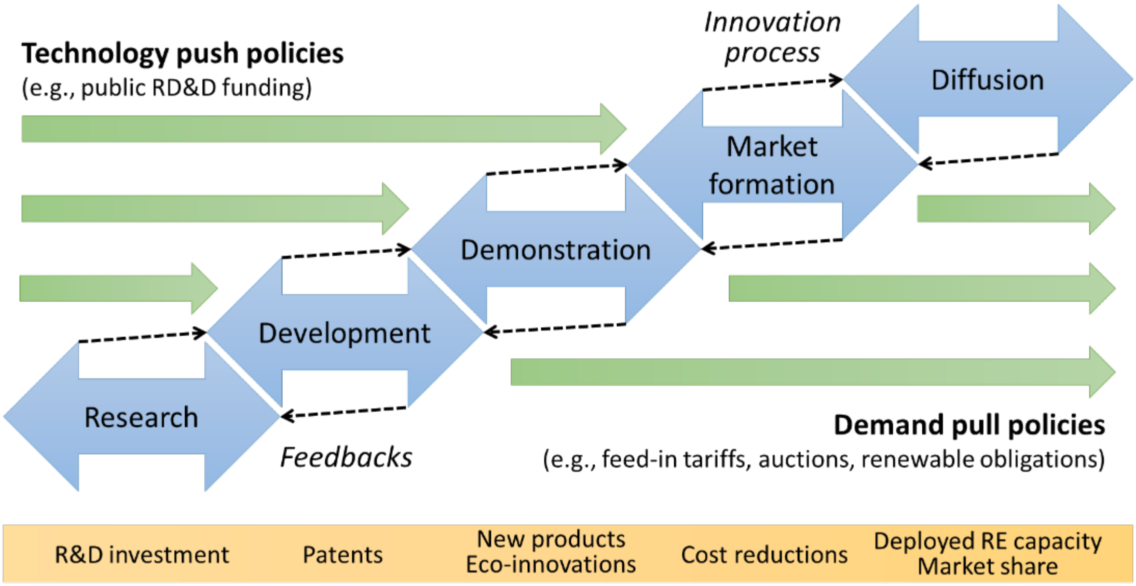

Fig. 1. Technology innovation process, stages, policies and indicators. The stages are the blue arrows, the indicators used to describe progress in each stage are in the yellow rectangle, and the green arrows denote technology push and demand-pull policy instruments. Source: adapted from Grübler et al. (2012) with own elaboration on innovation indicators based on combined evidence from Peñasco et al. (2021) and Grubb et al. (2021).

Technology push policies, e.g. public RD&D funding; and demand-pull policies, e.g. FITs, RE auctions, or renewable obligations, have long been mentioned by the ex-ante literature as potentially important drivers of innovation. These policies help

[4] In collaboration with other EEIST researchers, the authors designed and implemented a survey of technoeconomic models that inquired how the models represented different policies, mechanisms and outcomes related to innovation and competitiveness. Responses cover the following 16 models: E3ME+FTT; DSK; EPS India 2.1.2; TeFE ABM; K+S ABM; AgriLOVE; ERRE; GIBM; GEM; ICEM; TFR Disaggr; C-GEM China; IPAC; TERI CGE; MARKAL India; Balmorel.

[5] Grübler, A., Aguayo, F., Gallagher, K., Hekkert, M.P., Jiang, K., Mytelka, L., Neij, L., Nemet, G., and Wilson, C. (2012). *Policies for the energy technology innovation system (ETIS)*, pp: 1665-1744.

overcome environmental and knowledge externalities, information asymmetry and network effects, and other barriers that exist between the stages of innovation. Until recently, however, there had been little effort to synthesize the ex-post evidence from policies implemented in different countries around the world regarding the impact that these policy instruments have had on different innovation indicators.

3. Innovation outcomes and indicators

Evaluations of decarbonisation policies on the ground now cover a wide range of innovation indicators.

A comprehensive analysis conducted by EEIST researchers indicates that we now have conclusive empirical evidence from policies 'on the ground' regarding the positive impacts of decarbonisation policies on technology innovation indicators, especially when it comes to their impact on expanding renewable energy deployment and market share. Evidence derived from Peñasco et al. (2021) shows that more than 150 evaluations of decarbonisation policies focus on understanding the impact of the policy on increased deployment of a technology or set of technologies (Fig. 2).

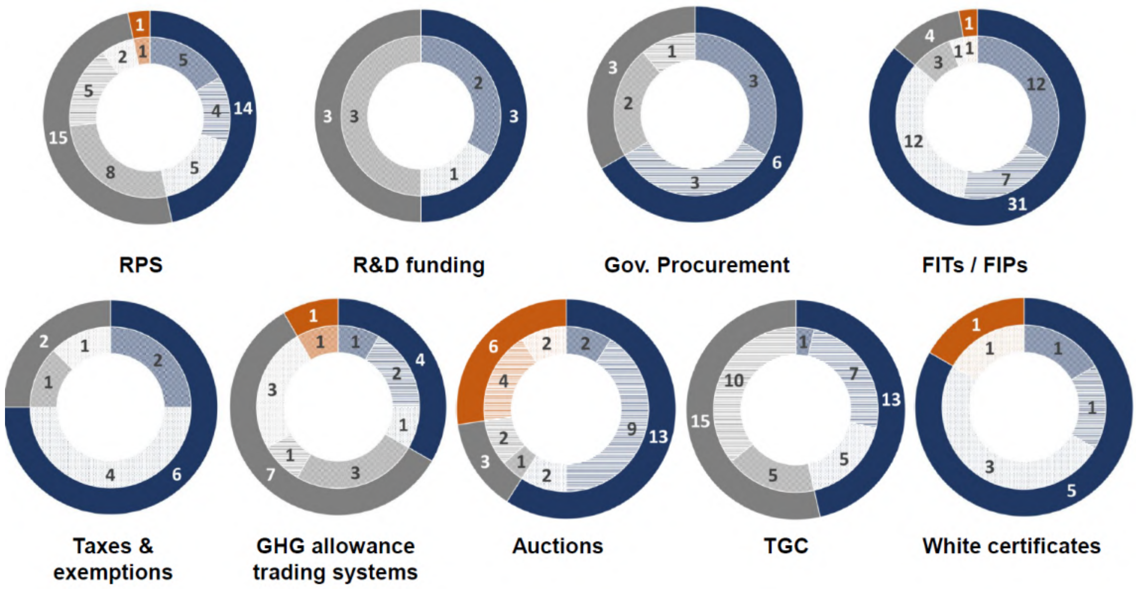

Fig. 2. Impact of the ten policy instruments on the technological effectiveness (deployment) outcome. The outer circles represent the number of positive impact (blue), no impact (grey) and negative impact (orange) evaluations by type of policy instrument. The inner circles represent the type of methodology 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. RPS stands for Renewable portfolio standards; FITs/FIPs – Feed-in tariffs and premiums; GHG – Greenhouse gas; TGC – Tradeable green certificates. Source: Peñasco et al. (2021).

However, innovation outcomes are not restricted to the last stages of innovation, i.e. to technology deployment. The evidence from the policy evaluations on the ground shows that the innovation benefits from decarbonisation policies go beyond the deployment of the technology itself, resulting also in the creation of new products, processes and services; technology cost reductions and performance improvements, and additional research and technology spillovers that affect domestic capacity in other technologies and sectors. Indeed, there is plenty of evidence regarding the impact of different decarbonisation policies on other broader indicators of innovation associated with economic growth and opportunity (Fig. 3).

Fig. 3 combines evidence for innovation indicators derived from Peñasco et al. (2021) and Grubb et al. (2021). Almost 40 papers—mostly relying on quantitative analysis—indicate a positive impact of decarbonisation policies on patenting, which is an indicator associated with the ability to generate new products and also a proxy for technological competitiveness. This is followed by 24 publications that cover results on technology cost reductions, an indicator of innovation associated with economic and fairness benefits.

There is also significant quantitative literature (16 papers) indicating that decarbonisation policies have positive impacts on “eco-innovation” indicators, which track the emergence or switch to new or existing "green" products. 12 publications link policies to increases in private R&D in clean technologies, which is associated not just with future products but also capacity building. All of these indicators can result in knowledge spillovers to other technologies and sectors. This means that the innovation benefits from the policies go well beyond incentivising technology deployment.

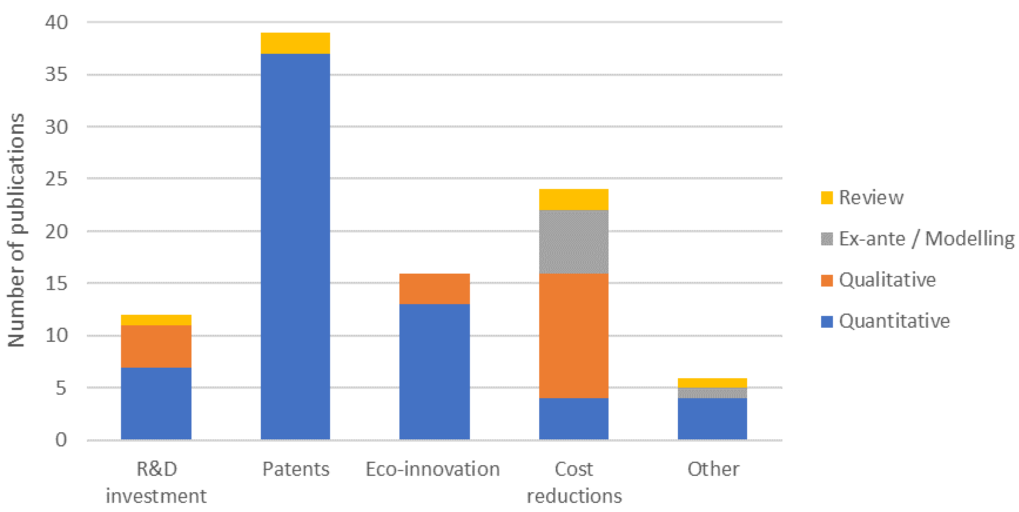

Fig. 3. Number of publications evaluating the impact of different decarbonisation policies on different innovation indicators by research methodology. The innovation indicators covered are increased private R&D investment, patents, eco-innovations, cost reductions, technology diffusion, and other (e.g. publications). The colours denote the research methodology that produced the policy evaluation. All but the grey areas denote ex post evaluations. Source: own elaboration with combined evidence on innovation indicators from Peñasco et al. (2021) and Grubb et al. (2021).

4. Policy instruments and impacts

For most policy instruments, the impact on innovation indicators is conclusively positive.

Letting aside technology deployment, the evidence of the impact of various decarbonisation policy instruments on the sum of all the innovation indicators listed in Fig. 3 is summarised by the direction of impact (positive, null or negative impact[6]) in Fig. 4 and further broken down for each policy by indicator and direction of the impact in Fig. 5.

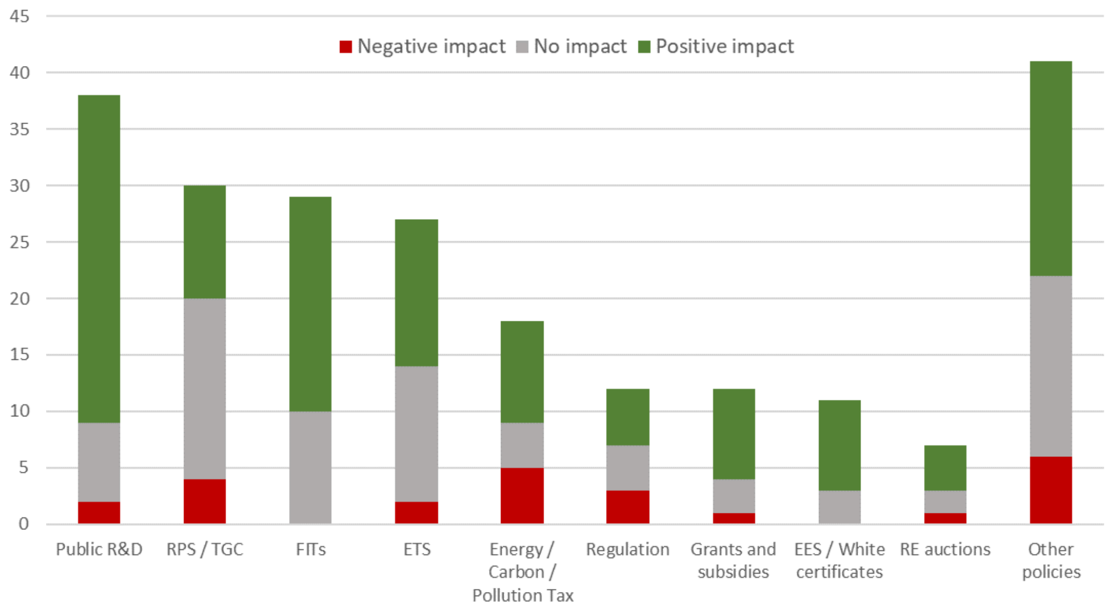

Fig. 4. Number of evaluations on the impact of different policy instruments on all innovation indicators combined. Grey denotes negligible impact, green positive impact and red negative impact when compared to a particular counterfactual as explained in the text. In the figure and below, RPS / TGC denotes Renewable portfolio standards and Tradeable green certificates; FITs – Feed-in tariffs; ETS – Emissions trading scheme; EES – Energy efficiency standards; RE auctions – Renewable energy auctions. 'Other policies' aggregate evidence of impact of the following policy instruments with less than 5 evaluations each: tax allowances; fuel mandates; public procurement and investment; RE and electric vehicle (EV) targets; intellectual property (IP) agreements; and other unspecified soft instruments, demand-pull policies, capital investment incentives (e.g., investment tax credits), and production-based financial incentives (e.g., production tax credits). Source: own elaboration with combined evidence on innovation indicators from Peñasco et al. (2021) and Grubb et al. (2021).

[6] In the context of innovation outcomes, negative impact of policy represents relatively less innovation compared to the baseline scenario or other policies rather than its suppression in absolute terms. In some cases it may mean that a policy resulted in less disruptive and more incremental innovation compared to a particular counterfactual. Thus, the 'negative' impact represented in red in Fig. 5 should not be taken to mean that the policies curtail innovation more broadly.

Overall, we find:

1. Public R&D funding has a strong positive impact in promoting innovation outcomes. The analysis on the impact of Public R&D funding on innovation has been mostly focussed on understanding its impact on patenting indicators. Most importantly, although there is comparatively less evidence, research shows that public R&D investments play a role as catalysers of R&D investment in the private sector with very limited evidence supporting the existence of crowding out effects. This suggests that public R&D investments in energy spur domestic private innovation and competitiveness (See Fig. 5).

2. Deployment incentives, e.g., FITs and RE auctions have played a positive role across all stages of the innovation process. FITs, RE auctions, EES and white certificates are associated with positive impacts on clean technology patents and cost reductions, as well as deployment (See Fig. 2 and 5). There is more mixed evidence regarding the impact across different innovation indicators for renewable portfolio standards and tradeable green certificates (RPS / TGC).

3. FITs have been a critical instrument for supporting innovation across the whole process. Its impacts have varied by technology but generated the strongest positive impact on solar photovoltaics.

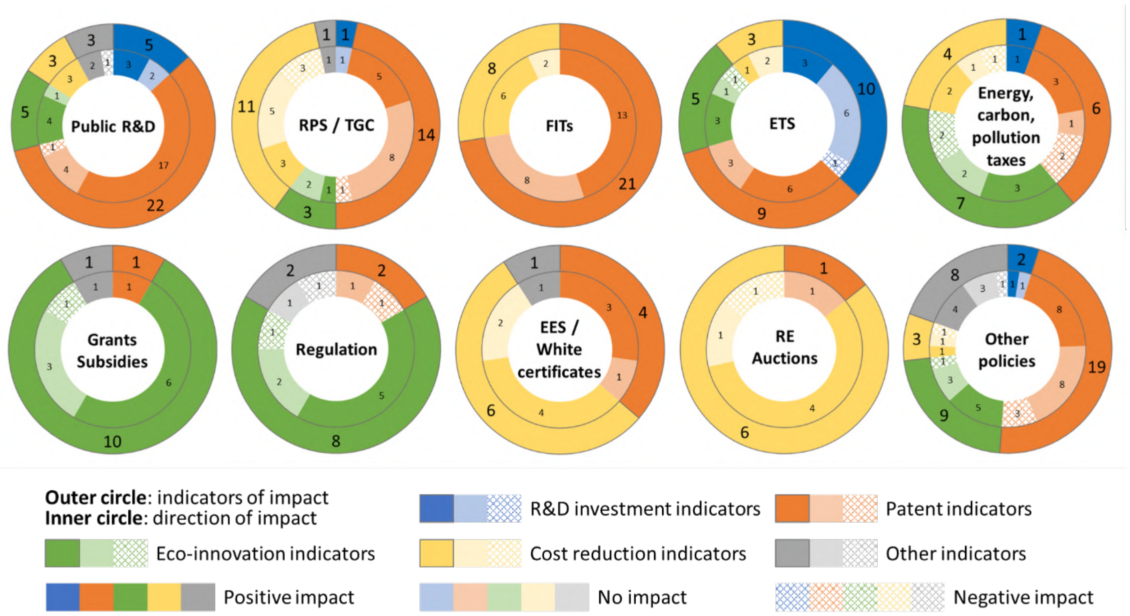

Fig. 5. Number of publications evaluating the impact of 10 types of policy instruments on different innovation outcomes by innovation indicator and direction of the impact. The innovation indicators are: private R&D investments (blue), patents (orange), eco-innovations (green), cost reductions (yellow), and others (grey). In the inner circle, positive impacts are in solid colours, negligible impacts are faded, and negative impacts are represented with crossing lines. The majority of impacts are shown in solid colours, which means that the impacts are positive. Abbreviations for policy instruments are the same as in Fig. 4. Source: own elaboration with combined evidence on innovation indicators from Peñasco et al. (2021) and Grubb et al. (2021).

4. In 2017-2018, RE auctions were used in approximately 50 countries worldwide (IEA/IRENA, 2019). Given their use has become more pervasive only recently, available evidence mostly comes from case studies and qualitative research. Evidence of the impact of auctions in the early stages of technology innovation, i.e. beyond deployment indicators, is so far inconclusive and further research is needed. However, given the increase in the number of countries, above all in the Global South, using this type of mechanism, particular attention to this instrument is needed both in policy evaluation and in modelling.

5. Empirical evidence is inconclusive regarding the impact of carbon pricing mechanisms. Research has covered the impact of both emission trading schemes (ETS) and energy, carbon and/or pollution taxes, on innovation. The innovation impacts of taxes have been measured mostly through patenting and eco-innovation outcomes. While some evaluations identify positive impacts (50%), further research is needed. The evaluations of ETSs show null or positive impacts on R&D investment, patenting and eco-innovation. For ETSs, 48% of evaluations are positive and 52% negligible or negative. Most evidence on these schemes covers previous time periods with lower carbon prices and experiences from industrialized countries.

6. There is significant literature on the impact of broader policy categories, e.g. grants and subsidies or regulation, among others, on broad eco-innovation indicators that cover the emergence and adoption of new "green" products. Grants and subsidies are relatively consistently associated with positive impacts on eco-innovation. In contrast, a lot of disagreement is found on the effect of regulation, perhaps due to the fact that 'regulation' is a very broad term and not well defined in the underlying studies.

5. Representation of policies in models

Models generally underestimate the economic benefits of decarbonisation policies because only some positive impacts are captured.

The reviewed empirical evidence strongly identifies policy-induced innovation impacts. Therefore, there is a need to ensure that existing technoeconomic models and policy analysis represent the most relevant policies to facilitate the energy transition and to capture the economic opportunities through innovation and capability development. Models should ideally capture not just deployment impacts but also the impact of policies on innovation indicators in different parts of the innovation process. Otherwise, model projections for a low carbon transition or for identifying areas of economic development and opportunity are likely to produce conservative and biased near-equilibrium predictions that consistently underestimate the pace of technological innovation and its radical systemic impact on decarbonisation. This will negatively affect the decision-making processes by policymakers around the world.

A survey of 16 technoeconomic models conducted by EEIST researchers explored the representation of technological change, innovation, competitiveness and decarbonisation policies in these models. This survey found that while technoeconomic models often include some important decarbonisation policy instruments, e.g. carbon taxes, models are not always accurate in the representation of the key role played by demand-pull policies, e.g. FITs and RE auctions, in stimulating rapid cost declines and capacity deployment in renewable energy (see Fig. 6).

The results show that some models aim to reflect the effect of policies on technology diffusion or renewable energy capacity deployment, either directly by stimulating demand, or indirectly through their effect on cost reductions or price elasticities. Specifically, from the set of models surveyed through the EEIST project, only 8 out of 16 represent some innovation indicators. Out of this, most consider the impact of some policies on deployment and cost-reduction indicators. However, other innovation impacts of decarbonisation policies are very often missing. In many instances, models also do not account for dynamics of endogenous technological change, do not represent technology and knowledge spillovers to other sectors or assume that cost reductions happen over time through public R&D investments (Grubb et al. 2021).

Importantly, we find that the models do not currently cover the full set of decarbonisation policies for which strong evidence is available regarding their impact on innovation. As shown in Fig. 6, taxes, carbon prices and deployment subsidies (which could include FITs) are relatively well-represented in the models, while some policies that have clear evidence of impact on innovation, such as Public R&D and FITs, are relatively less represented. Interestingly, some surveyed models aim to model policies that lack empirical evidence about their innovation impacts, such as building codes and standards, fuel economy and standards, and loans or soft loans. The inclusion of these policies in the models offers a unique opportunity to close the existing evidence gap in cases where empirical evaluations are not yet available.

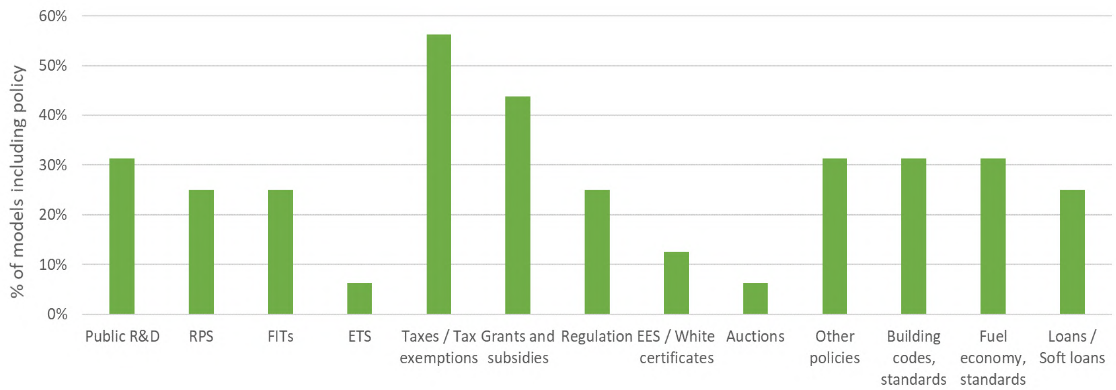

Fig. 6. Percentage of energy-economic decision-support models representing different policy instruments (N_{models} = 16). Abbreviations are the same as in Fig. 4. *Other policies* include product standards; government procurement; green finance policy; and forest restoration. Source: Own elaboration from survey results.

6. Lessons learned

First, the underestimation of technological change by experts and most quantitative approaches, the new evidence regarding the positive impact of decarbonisation policies across all stages of innovation (beyond diffusion), and the underrepresentation of these various innovation processes in economic models suggests that the current basis for decision making is biased against correctly estimating the opportunities and economic benefits from decarbonisation policies.

Second, there is a need to improve the assumptions about energy technology cost reductions in modelling tools.

Third, dynamic benefits from decarbonisation policies on new products, private R&D and spillovers across sectors must be considered. The representation of a broader set of policies is also essential. Without considering these new developments, the energy policy process is normally unnecessarily conservative and biased against policies that could promote important growth opportunities.

Having said that, gaps to be filled by future research are identified both in the empirical evaluation of additional policy instruments (most notably in developing country contexts) and also in a more comprehensive representation of the ways in which different policies shape innovation and competitiveness outcomes. In particular, empirical research and modelling on the impact on innovation of product efficiency regulations, building codes and standards, fuel efficiency mandates and standards, public procurement, soft instruments, and green financing tools such as loans and loans guarantees would better reflect the dynamic nature of the energy transition and the growth and wellbeing opportunities that can be realized through different policies.

APPENDIX

1. The geographical context

The available evidence of the impact on innovation indicators of decarbonisation policies covers more than 30 countries (Fig. A1). Most papers analyse policy instruments and outcomes at the national level in OECD countries, with the United States (15), the United Kingdom (24) and several EU countries—Germany (16), Italy (10), Sweden (10), Spain (10), France (9) or Belgium (8), being the most frequently studied. Eight publications cover China, two – India, and two – Brazil at the national level.

A very small number of papers focus on less developed countries highlighting a large gap in the geographic coverage of the literature.

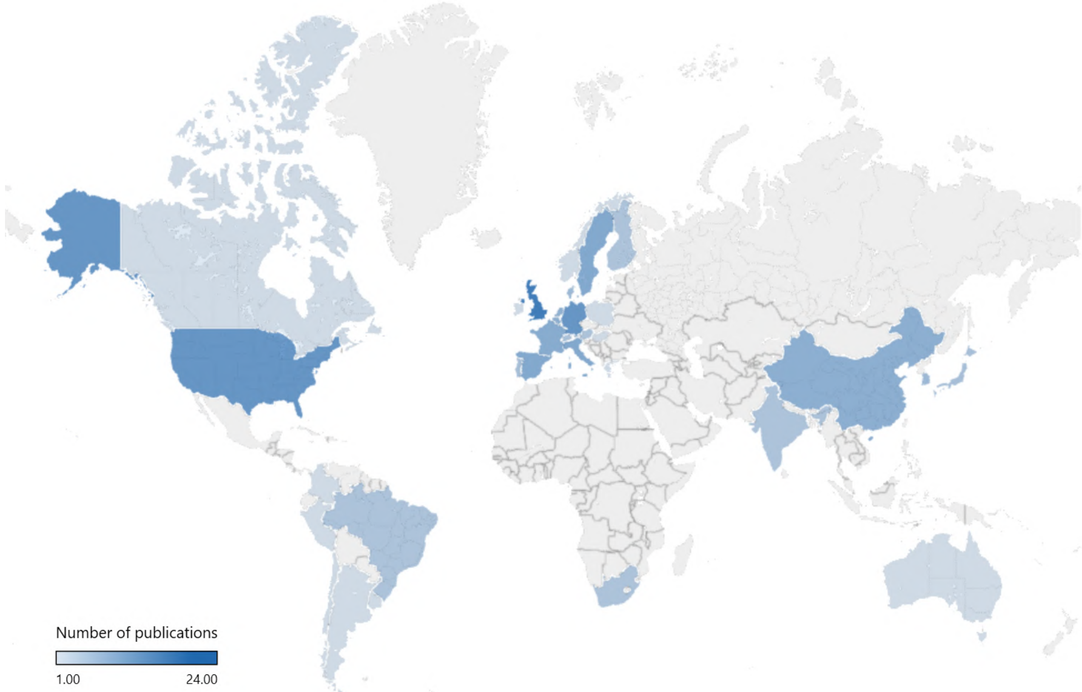

Fig. A1. Geographical scope of the literature evaluating the impact of decarbonisation policies on different innovation indicators. N = 94 papers. Source: Own elaboration with combined evidence on innovation indicators from Peñasco et al. (2021) and Grubb et al. (2021).

2. Comparison of expert- and model-based forecasts

Fig. A2 below shows a comparison of expert- and model-based forecasts to 2030 for key energy technologies (Meng et al. 2021). In almost all cases experts expect a slower pace of innovation compared to model-based forecasts. Given that model-based methods perform better, relying on 2030 expert estimates would result in an underestimation of technology cost reductions.

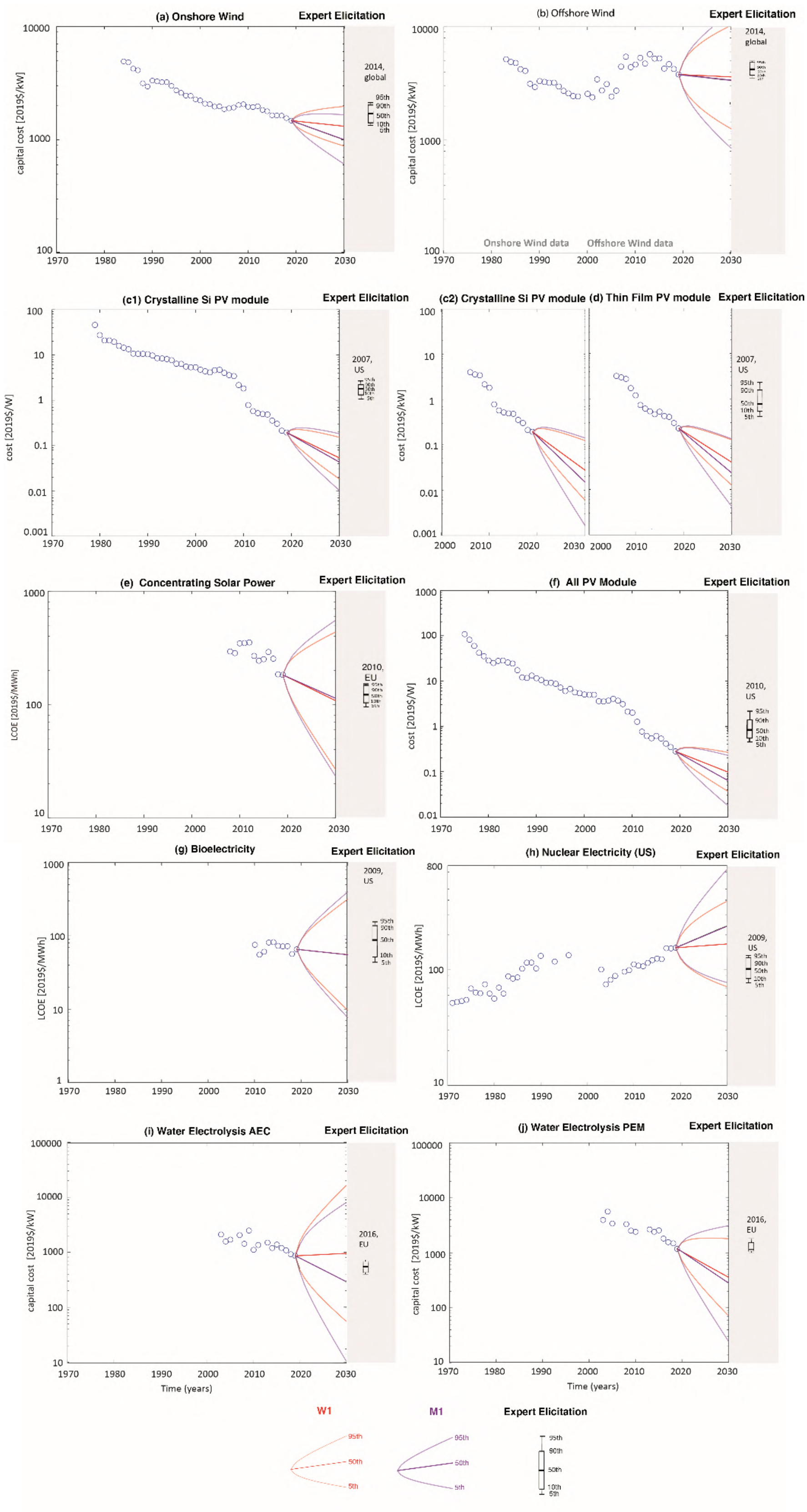

Fig. A2. Comparison of probabilistic 2030 technology cost forecasts from experts and from model-based methods showing that expert forecasts tend to be more pessimistic. W1: forecast using Wright's law, i.e., costs as a function of deployment, and M1: forecast using Moore's law, i.e., costs as a function of time. Source: Meng et al. (2021).